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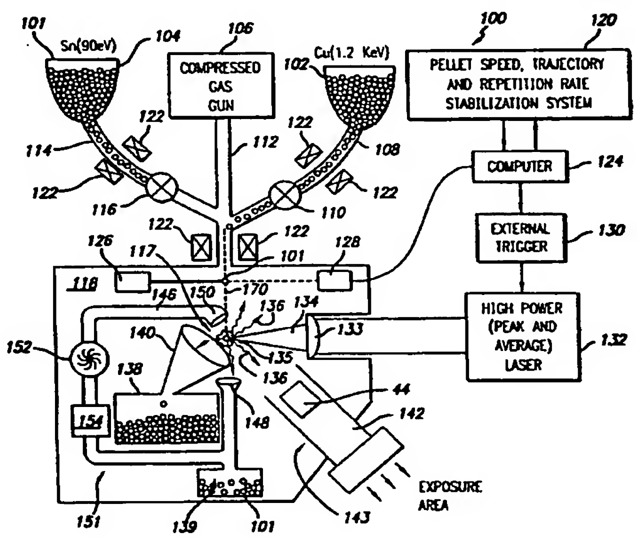

(57) Abstract: A system and method for generating radiation of a desired wavelength is provided by irradiating microtargets (101, 210). These microtargets (101, 210) are selected from any material that will emit radiation of the desired wavelength. A dispensing apparatus (100, 200) delivers a microtarget into an irradiation zone, where the microtarget is irradiated by an energy source (132). The microtarget (101, 210) may be dispensed in liquid or solid form. Once formed, the desired radiation is directed from the irradiation zone to a beamline while a debris removal arrangement that is in communication with the irradiation zone (117), the energy source (132), and the beamline (142) substantially prevents debris and other pollutants from contaminating the system equipment.

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METHOD AND RADIATION GENERATING SYSTEM USING MICROTARGETS

Priority is claimed from Provisional Application Ser. No. 60/161,891, filed October 27, 1999, entitled "Laser Plasma X-ray Generating System and Method of Using Solid Micropellet Targets" and which is referred to and incorporated herein in its entirety by this reference.

Field of the Invention

The present invention relates to radiation generation, and more particularly to a method and system for generating radiation using a microtarget. In a preferred embodiment, the present invention is shown as a system for generating x-ray, extreme ultraviolet (EUV), vacuum ultraviolet (VUV), or ultraviolet (UV) radiation by irradiation of a microtarget.

Background of the Invention

Various methods and systems are known for generating radiation. For example, x-rays may be generated by striking an x-ray generating target material with a form of energy such as an electron beam, a proton beam, or a light source such as a laser. Various forms of x-ray generating targets are known. These known systems and methods typically irradiate gases, liquids, frozen liquids or solids to generate the x-rays. Current systems that use either room temperature liquid or gas targets impose severe limitations on the type of chemical elements or materials that can be irradiated because many elements are not in the liquid or gaseous state at ambient pressure and temperature. Hence, the range of desired x-ray wavelengths achievable by either gas or liquid systems is also limited.

In an attempt to overcome this limitation, other systems dissolve solid materials, e.g., copper, into a chemical solvent such as sulfuric acid. Desirable solid materials are solids at ambient temperature and pressure, and will emit the desired range of x-ray wavelengths when irradiated. Once in solvated liquid form, these materials are irradiated as liquid or frozen liquid particle targets. The liquids are in essence solid metal solvated by liquid solvent. Thus, the drop of liquid or frozen

liquid particle serving as the target typically is composed primarily of the solvent. When irradiated by a laser beam or pulse, the majority of material being heated is the non-x-ray generating solvent rather than the solid dissolved in the solvent. This leads to a large amount of emissions in undesired spectral regions, along with emissions produced by the solid and these systems tend to be inefficient x-ray generators. Additionally, these systems suffer from the deleterious effects of solvating liquids such as sulfuric acid. For example, such solvating liquids can be toxic, difficult to dispose of, and can cause corrosion damage to the x-ray generating equipment and machinery, thereby shortening the lifetime of the system.

One type of prior x-ray generating system uses frozen water particles as the target. This system does not have the problem of removing sulfuric acid or other solvating liquids as a contaminant. However, this system is limited to producing x-rays in the 11.9 to 13 nanometer (nm) spectral range, or by increasing laser intensity on the target, producing x-rays in the 1.5 to 2.2 nm spectral range. Disadvantageously, the spectral range achievable by frozen water targets tends to be limited and the efficiency in converting laser irradiation to x-ray radiation tends to be low.

Another x-ray generating system uses an ethanol liquid as the target material. The target is dispensed from a jet nozzle as liquid droplets and are very small compared with the size of the laser beam diameter. This system typically does not suffer the deficiency of harmful solvents and because of the small droplet size, the target typically can be completely ionized, substantially eliminating problems associated with debris removal. However, because of the heat generated by the laser system, much of the unirradiated ethanol vaporizes or otherwise evaporates, thereby typically causing vacuum difficulties and moisture problems for the electronic equipment. Additionally, because of the inherent chemical properties of ethanol, this system does not produce x-ray emissions below the 3 nm wavelength desirable for microscopy applications. Accordingly, it is a deficiency in the know x-ray generation systems using ethanol liquid system that there desired x-ray wavelength emissions are not generated and there is a need for a system with a liquid generation system producing x-rays in desired wavelengths.

Solid materials provide a wide range of x-ray emissions currently unavailable in materials that are in a liquid state at ambient temperature and pressure. One type of prior x-ray generation system uses solid blocks of material (e.g., copper) to generate

laser plasma x-rays. In this system, a block of material remains stationary in the irradiation area while laser beam pulses repeatedly irradiate the block of material to produce a plasma. The laser beam generates temperatures well over one million degrees Kelvin and pressures well over one million atmospheres on the surface of the material. These extreme temperatures and pressures cause ion (e.g., copper ion) ablation and strong shocks into the solid material. Ion ablation from the surface of the target material at very high speeds and temperatures causes contamination within the x-ray chamber as well as to other system equipment such as the x-ray collection system and the optics associated with the laser. Thick solid targets induce shock waves that reflect back from the target surface and splash the x-ray chamber with target debris. Ion ablation and target debris decrease the efficiency of the system, increase replacement costs, and shorten the lifetime of the optical and laser equipment.

Another form of solid target material is a very thin tape of target material (e.g., copper tape for 1 nm x-rays). A roll of target tape is typically one-half inch in width and approximately 10-20 microns thick. The roll of target tape is dispensed at a predetermined rate while a laser beam pulse irradiates and heats the tape at a desired frequency. The fast ions ablated from the target surface are ejected away from the target. The plasma-generated shock wave breaks through the tape and ejects most of the target material at the back of the target where it can be collected. Thus, use of this tape target substantially reduces ion contamination within the x-ray chamber when compared with solid blocks of target material.

The use of a thin tape target does not completely eliminate target debris at the laser focal point of the target tape. To eliminate or further reduce material contamination within the x-ray chamber, the x-ray chamber is filled with helium at atmospheric pressure. Helium circulated within the x-ray chamber removes the ablated ions. As ions are ablated from the target material, helium atoms collide with the high-velocity ions, stopping the ions within a few centimeters from the target position. As the helium gas/ion mixture is re-circulated within the x-ray chamber, filters trap the ions, recirculating only the helium gas at the completion of the filtration process. The use of thin tape targets and helium gas to stop ablated ions from contaminating the x-ray chamber is described in more detail in Turcu, et al., High Power X-ray Point Source For Next Generation Lithography, Proc. SPIE, vol. 3767, pp. 21-32, (1999). Unfortunately, significant amounts of target debris are still

produced in cooler portions of the laser beam. Moreover, this system does not provide mechanisms that deflect target debris away from optics, and other expensive equipment used in generating radiation.

Current systems and methods utilizing thin tape targets suffer additional disadvantages. The types of materials that are commercially available in thin tape form are limited. Additionally, thin tape targets require a large tape-dispensing apparatus, which utilizes a significant amount of space within the x-ray chamber, substantially adding to the size and space requirements of such x-ray generators. Tape targets also require frequent reloading of new tape material, which disrupts the operation of the x-ray generator. For example, a reel of thin tape target material having a length of approximately one mile, with a reel diameter of approximately eight inches, typically needs to be replaced with a new reel of tape after a few days of continuous x-ray generation.

In view of the deficiencies of the known methods and systems described above, a need exists for a method and system that provides radiation in a large variety of wavelengths, with minimum target debris and equipment contamination, and further provides radiation generating targets that are renewable, preferably inexpensive, generally available, easy to handle and transport, compatible with to commercial applications, and allow for relatively prolonged periods of radiation generation.

Summary of the Invention

It is therefore an object of the present invention to provide a system and method of generating radiation in a wide range of wavelengths using targets that are renewable, generally available, inexpensive, easy to handle and transport, and allow for relatively prolonged periods of radiation generation. It is a further object to substantially prevent target debris from contaminating system equipment. The present invention significantly alleviates the disadvantages of known radiation generation systems by providing radiation-generating microtargets.

Briefly, a system and method for generating radiation of a desired wavelength is provided, which makes use of microtargets. These microtargets are selected from any solid or solid material in a molten state that will emit radiation of the desired wavelength. A dispensing unit, such as a apparatus, delivers a microtarget into an irradiation area, where the microtarget is energized by an energy source. The microtarget may be dispensed in liquid or solid form. Once formed, the desired

radiation is directed from the irradiation area to a beamline while a debris removal arrangement that is in communication with the irradiation zone, the energy source, and the beamline substantially prevents debris and other pollutants from contaminating the system equipment.

One advantage of the present invention is that microtargets formed from solid materials in accordance with the present invention can produce a wide spectral array of wavelengths and energies available with solid materials. For example, hard x-rays, soft x-rays, extreme ultraviolet (EUV), vacuum ultraviolet (VUV), and ultraviolet (UV) radiation may all be produced from solid materials by irradiating microtargets at different energy intensities. For example, tin microtargets may be used to produce EUV radiation at ~0.1 keV or ~4.0 keV x-rays. Similarly, copper microtargets may be used to produce soft x-rays with energies of ~1 keV, hard x-rays of ~8.9 keV, or radiation emissions along a continuum, such as Bremsstrahlung radiation extending to ~100 keV or higher. By contrast, very limited number of elements exist in the liquid or gaseous state at ambient temperature and pressure, which inherently limits current liquid or gaseous x-ray systems.

In one preferred embodiment, the solid microtarget material is heated to a molten, i.e. liquid, state and used in the liquid state. Because the microtarget material is dispensed as a. liquid droplet, the liquid microtarget is uniformly spherical in shape, and this creates an advantage over existing solid targets by increasing the accuracy in positioning the laser beam, and more accurately calculating the trajectories of the target debris and radiation emission, thereby maximizing production efficiency and aiding in preventing contamination of the system equipment with target debris. Solid targets typically have non-uniform surface structures that decrease the accuracy in predicting debris and x-ray emission trajectories.

Another advantage of the present invention is that advantages of a liquid system can be achieved while generating a wider range of wavelengths. Advantageously, the liquid microtarget is formed completely from molten solid, thus obviating the need of a dissolving solvent such as sulfuric acid. Accordingly, the present invention avoids the problems associated with irradiating a target primarily composed of solvent, such as unwanted spectral emissions as well as the corrosive effects of sulfuric acid, or other solvating liquids. A further advantage stems from a solid's chemical properties that prevent vaporization and evaporation of unused target

material, thus eliminating the vacuum and moisture problems encountered by current liquid systems.

In a preferred embodiment of the present invention, debris typically associated with solid micropellets is reduced. In this embodiment, the small size of micropellets used achieves a reduced amount of target debris generated than typically might be expected when a solid block of target material is used. Micropellets also may be dispensed in compact reservoirs that allow for continuous radiation generation over extended periods, such as several weeks or months, if not longer.

Advantageously, the present invention also employs a debris removal arrangement that substantially prevents target debris from contaminating system equipment. For example, in one embodiment, supersonic gas jets sweep debris away from the irradiation area. Another embodiment uses gas to collide with ablated ions before the ions can contaminate system equipment. Yet another embodiment utilizes a shock wave to create a region of higher density gas to stop ablated ions. Other embodiments of the present invention use electric fields, magnetic fields and/or temperature gradients in order to deflect target debris from system equipment.

The present invention may be utilized in any production, system or process requiring radiation generation. For example, x-ray, EUV, VUV and UV radiation generated by this invention may be used in lithography applications. In particular, the x-ray emissions of ~1 keV energy are very important for x-ray lithography. Likewise, ~0.1 keV emissions is a desired feature in EUV lithography, particularly in conjunction with molybdenum silicon mirrors. As another example, semiconductor, pharmaceutical, medical, and chemical applications abound for using x-rays generated by this invention.

In one aspect of the invention, a radiation generating system using a microtarget including a solid material is provided, the system comprising: a dispensing apparatus dispensing a microtarget on a microtarget path; an energy source, emitting an energy beam along an energy path; an irradiation area, positioned in the energy path and in the microtarget path, the microtarget path intersecting the energy path within the irradiation zone; a beamline, configured to receive radiation generated in the irradiation zone; and a debris removal arrangement along the micropellet path, downstream of the irradiation zone. It should be appreciated that the "solid material" preferably is a material that is in a solid state in an ambient condition. However, in the context of the present invention, a "solid material" is defined to

include and may also include materials in a molten or liquid, state. Where the microtarget is in a liquid state, the microtargets delivered by the dispensing system comprise droplets.

In another aspect of the invention, a method of generating radiation using microtargets is provided, the method comprising all or a portion of the following steps: selecting a solid material that will generate radiation of a desired wavelength when irradiated by an appropriate energy source; providing the solid material as a discrete microtarget; delivering the microtarget into an irradiation zone; irradiating the microtarget with an energy source along an energy path such that irradiation produces radiation of the desired wavelength; directing the radiation emitted from the microtarget along a beamline path into a beamline; and removing target debris from the energy path and the beamline path. It should be appreciated that in an alternative embodiment of this aspect of the invention that the solid material is provided in a molten or liquid state. In such a case, the microtarget is in the form of a liquid droplet.

These and other features and advantages of the present invention will be appreciated from review of the following detailed description of the invention, along with the accompanying figures in which like reference numerals refer to like parts throughout.

Brief Description of the Drawings

FIG. 1 is a system diagram of various components and structures of a radiation generation system using solid micropellets as microtargets, in accordance with one embodiment of the invention;

FIG. 2 is a system diagram of various components and structures of a radiation generation system using liquid microtargets in accordance with an embodiment of the invention;

FIG. 3 is a system diagram of various components and structures of a radiation generation system using liquid microtargets in accordance with another embodiment of the invention;

FIG. 4 is a system diagram of various components and structures of a radiation generation system using a supersonic jet system in accordance with an embodiment of the present invention;

FIG. 5 is a system diagram of various components and structures of a radiation generation system using a supersonic jet system and blunt body duct to create differential pressure areas, in accordance with an embodiment of the invention;

FIG. 6 is a flowchart illustrating method of generating radiation of a desired wavelength using microtargets, in accordance with an embodiment of the invention;

FIG. 7 is a system diagram of various components and structures of a radiation generation system using a closed loop circulation system, in accordance with one embodiment of the invention; and

FIG. 8 is a system diagram of various components and structures of a radiation generation system using an electron beam as an energy source, in accordance with one embodiment of the invention.

Detailed Description of the Invention

The present invention provides a method and system of producing a variety of radiation emissions generated from plasma-induced microtargets. Speaking generally, the system is comprised of a microtarget or microtarget stream including microtargets formed from a solid or molten material, a microtarget dispensing apparatus preferably dispensing microtargets on a microtarget path, an irradiation zone or zone, an energy source preferably providing an energy beam on an energy path, a beamline, and a debris removal arrangement, although other arrangements or additional elements also may practice the invention.

Microtargets may be formed from any desired material that emits radiation of a desired wavelength when irradiated by an appropriate energy source. Preferably a solid material (in solid or molten state) is used. For example, using a laser to induce L-shell emissions, Copper (Cu) microtargets emit ~1.1 keV x-rays, Nickel (Ni) emits ~1.0 keV x-rays, Zinc (Zn) emits ~1.2 keV x-rays, Gallium (Ga) emits ~1.3 keV x-rays, Germanium (Ge) emits ~1.4 keV x-rays, Indium (In) emits ~4 keV x-rays, and Tin (Sn) emits ~4 keV x-rays. It will be appreciated that other emissions at different energy levels may also be induced. For example, by irradiating at higher laser intensities, K-shell emissions at ~8.9 keV or Bremsstrahlung radiation at ~50 keV, or higher, may be generated from Cu. As other examples, K-shell emissions may be induced from Beryllium (Be) (~0.1 keV), Boron (B) (~0.2 keV), Carbon (C) (~0.3 keV), Chlorine (Cl) compounds (~2.8 keV), Titanium (Ti) (~4.8 keV), Gallium (Ga) (~10 keV), or Indium (In) (~29 keV) microtargets. When irradiated with the

appropriate energy source, tin (Sn), Indium (In) or Stibium (Sb) microtargets generate a band emission ranging approximately between 13 nm and 14 nm (~0.1 keV EUV radiation).

Many solid materials emit multiple wavelengths, depending on the energy intensity of the irradiation source. For example, Indium (In) emits ~0.1 keV, ~4 keV, and ~29 keV radiation depending on the intensity of the irradiation source. Likewise, Ga is capable of emitting energies of ~1.3 keV, ~10 keV, and ~54 eV, among others. By coupling the irradiation source to a grating and spectrometer in one embodiment, these multiple wavelengths may be generated from the same microtarget without needing to adjust the system configuration. It will be appreciated that alloys also may be used as microtargets. Any material that will emit radiation of a desired wavelength when irradiated by an appropriate energy source may be selected as suitable microtarget material.

FIG. 1 illustrates an apparatus 100 in which the microtargets are formed from solid micropellets, in accordance with a preferred embodiment of the invention. The apparatus 100 includes a first micropellet target source bin 102 which contains solid micropellets made from a desired material such as copper (Cu). Apparatus 100 may include one or more additional micropellet sources, each containing a unique type of micropellet material in order to achieve a variety of spectral wavelengths. FIG. 1 illustrates a second micropellet source 104 containing tin (Sn) micropellets. In a preferred embodiment of the invention, the first micropellet source 102 contains microspheres of copper (Cu), which generate x-rays having an energy of approximately ~1.2 keV, and the second micropellet source 104 contains tin (Sn) microspheres, which generate ~80-120 eV (EUV) radiation.

It is preferred that the micropellets 101 in the micropellet source bins 102 and 104 have of a generally uniform size and shape, largely spherical with a diameter of 10 to 100 microns, and free of any surface contaminants, debris, or irregularities. Such micropellets 101 can achieve substantially uniform velocities and trajectories when propelled into radiation chamber 118 and irradiation area 117 (also referred to as irradiation zone 117). One method of obtaining spherical micropellets of uniform size and shape is to use an apparatus known as a "drop tower." By melting a desired material such as copper, for example, the resulting liquid is sifted through a mesh having a desired granularity. As the liquid copper, for example, flows through the mesh, small copper droplets are formed. As the droplets fall from the mesh, they

oscillate and begin to solidify as they fall. The oscillation of the droplets as they fall causes the shape of the droplets to become uniformly spherical because of the liquid surface tension. In this way, spherical copper micropellets having substantially uniform size and shape can be obtained. The "drop tower" method and system are well-known in the art and, therefore, need not be further described herein. It will be appreciated that the present invention is not limited to any particular micropellet size or shape and that micropellets of any size or shape may be used in accordance with the invention.

The present invention further includes a dispensing apparatus, such as a apparatus for delivering the micropellets 101 to the irradiation area at a desired rate. For example, in apparatus 100, the dispensing apparatus includes a compressed gas gun 106 and gas-gun apparatus 112, which propels and injects the micropellets into irradiation area 117. In a preferred embodiment, micropellets leave first micropellet source 102 through a first conduit 108, which has a first opening at the bottom of first micropellet source 102. Preferably, the micropellets 101 travel through the first conduit 108, toward a first control valve 110, coupled to the first conduit 108, which opens and closes to either allow or stop the micropellets from entering a gas-gun apparatus 112 which extends downwardly from gas gun 106. In one embodiment, first control valve 110 automatically opens and closes under the control of a computer 124 (or other form of controller, electronic or otherwise) so as to automatically control the flow of micropellets from the first micropellet source 102. It will be appreciated that any type of conduit or control valve (or other dispensing apparatus) that will reliably deliver a microtarget into the irradiation area may be used. For example, conduit 108 may be a pipe, a capillary, a hose, a apparatus or any other conduit, constructed of any suitable material. Likewise, the control valve may operate, for example, robotically, magnetically, pneumatically, electronically or by any other method that can operate to sufficiently control the flow of micropellets 101.

As each micropellet 101 enters gas-gun apparatus 112, it is propelled downwardly by pressurized gas (e.g., helium) at a desired velocity toward irradiation area 117. The path of travel of the micropellet 101 from the dispensing apparatus (including gas-gun apparatus 112 in this particular embodiment) is characterized in this description as a micropellet path. One possible micropellet path is illustrated in the figures with dashed lines 170, although any desired path or trajectory from the dispensing apparatus to the irradiation zone can be used. The pressurized gas is

provided by a gas gun 106. It will be appreciated that this gas gun may be configured by any means known in the art that enables pressurized gas to deliver a microtarget 101 at a desired velocity. Alternatively, gravity may propel the microtargets into the irradiation area. In this disclosed example, the use of this pressurized gas to propel the micropellets toward an irradiation area 117 in the x-ray chamber 118 allows micropellets to successively reach irradiation area 117 at high repetition rates of 1 to 10^8 micropellets per second. It will be appreciated that higher and lower repetition rates may also be used. Depending on the repetition rate, a kilogram of micropellet microtargets can provide enough materials for continuous radiation generation for several weeks. This can present a significant improvement over prior thin tape systems, which require reloading of new target material after only a few days of continuous operation.

Micropellets 101 from the second micropellet source bin 104 travel down a second conduit 114, having an opening at the bottom of the second micropellet source 104, toward gas-gun apparatus 112. A second control valve 116, coupled to the second conduit 114, opens and closes to either allow or stop the flow of micropellets from the second micropellet source 104 into gas-gun apparatus 112. In one embodiment, computer 124 automatically operates second control valve 116 in order to automatically control the flow of micropellets from second micropellet source 104. As micropellets from the second micropellet source 104 enter gas-gun apparatus 112, they are successively propelled by means of pressurized gas from the gas gun 106 toward the target zone in the x-ray chamber 118, at repetition rates of 1 to 10^8 micropellets per second, and matched to a laser pulse frequency. FIG. 1 shows a preferred configuration in which second control valve 116 is in a closed state, thereby preventing micropellets in second conduit 114 from entering gas-gun apparatus 112 and first control valve 110 is in an open state, thus, allowing micropellets from the first micropellet source 102 to enter gas-gun apparatus 112. It should be appreciated that although reference number 101 is used herein for micropellets, micropellets designated with this reference number may be comprised of different as well as the same materials and may comprise different configurations and states, as well as the same configurations and states.

In an alternative embodiment, capillary tubes having a narrow interior channel are utilized for the conduits 108 and 114, and the gas-gun apparatus 112. By using capillary tubes having in internal channel diameter of approximately 100 microns, for

example, only one micropellet is permitted to travel through a given portion of the tube at a time. This allows a single micropellet to be introduced into radiation chamber 118 from gas-gun apparatus 112 at a single time.

The combination of the first micropellet source bin 102, the second micropellet source bin 104, the compressed helium gas gun 106, the first and second conduits 108 and 114, the first and second control valves 110 and 116, and gas-gun apparatus 112 comprise a preferred embodiment of the dispensing apparatus and is referred to herein as "microtarget insertion system" 119. It is understood that the disclosed microtarget insertion system 119 is but one example of a dispensing apparatus and many variations of the dispensing apparatus or dispensing apparatus may be implemented in accordance with the present invention. As such, any other system, such as an electromagnetic or electrostatic insertion system, a vibration system (e.g., ultrasound and/or piezoelectric crystal vibration systems) or a supersonic jet system, and any number or combination of micropellet source bins, conduits and control valves may be utilized in accordance with the present invention.

In one aspect of the microtarget insertion system 119, micropellets 101 are inserted with a generally stable trajectory with minimal variation in target position. For example, in one example, when a laser is used as the energy source, as in apparatus 100, the laser focal spot is less than $\pm$ 5 μm along the laser axis and no more than $\pm$ 10 μm perpendicular to the laser axis. As long as the micropellet trajectory is stable, the laser 132 or any other appropriate energy source can be focused on the micropellets 101 in the desired position at the beginning of the radiation generation process and will typically remain focused thereafter. Preferably, to reduce trajectory variation, an energy beam emanating from an energy source such as laser 132 is focused close to the micropellet insertion point.

Another desired feature of the microtarget insertion system is that it is capable of successively and repeatedly inserting individual micropellets at roughly the frequency required by a pulsed laser (e.g., 1 Hz to 100 MHz). To make up for small variations in injection repetition rate ($\pm$ 10%) the laser can be triggered by a firing device when the micropellet has been injected. In apparatus 100, the laser can fire within a very short time (nanoseconds) from a firing device such as receiving a signal from an external trigger 130.

As each micropellet enters gas-gun apparatus 112, it is propelled downward toward radiation chamber 118 and into irradiation area 117 by pressurized gas which is ejected from gas gun 106. In a preferred embodiment, the gas ejected by the gas gun 106 is helium, which is transparent to both incident laser light and the emitted x-ray radiation. When very soft (e.g., ~0.1 keV) x-ray radiation is desired, the helium pressure may be lowered, for example, to one atm. or one torr. Preferably, the type of gas is selected based on its ability to transmit the desired radiation (e.g., x-ray, EUV, VUV, or UV), as well as its ability to stop ablated ions. For example, helium gas has low density and high transmission to x-ray radiation, but other gases may be suitable depending on the radiation wavelength desired and the microtarget material used. Other gases such as, for example, krypton and hydrogen also may be used. It will be appreciated that any gas that effectively transmits the desired radiation may be used depending on the energy source and the desired radiation emitting from the microtarget.

Preferably, a detector system monitors the path of the microtarget in order to maximize irradiation efficiency. In apparatus 100, such a detector system monitors and/or stabilizes the speed, trajectory and repetition rate of the micropellets by the use of a Micropellet Speed, Trajectory and Repetition Rate Stabilization System 120 (hereinafter "the stabilization system 120"). Stabilization system 120 is electronically coupled to a plurality of actuators 122 positioned adjacent to first conduit 108, second conduit 114 and gas-gun apparatus 112. Actuators 122 may be coupled to the stabilization system 120 by any means known in the art, such as via physical wires, wireless technology, and analog or digital communications technologies known in the art, such that data may be transmitted between the actuators 122 and the stabilization system 120.

In one embodiment, actuators 122 may be sensors which can detect whether a micropellet is passing through a specified sensor area, measure the speed of the micropellet as it passes through the sensor area, and/or determine the trajectory of the micropellets. The actuators 122 may determine these parameters by, for example, high-speed photography techniques, electromagnetic techniques, magnetic techniques, motion detection techniques, or any method for detecting motion, measuring speed and/or determining object trajectories that are known in the art. In a preferred embodiment, after actuators 122 measure the speed and/or trajectory of the micropellets, actuators 122 convert the measured values into a predetermined data

format and transmit data representative of the measured values to the stabilization system 120.

Preferably, the stabilization system 120 receives data from actuators 122 and either processes the data by means of an on-board processor (not shown) within the stabilization system 120 or, alternatively, transmits the data to the computer 124 which processes the data and takes appropriate responsive actions in accordance with a program executed by the computer 124.

In one embodiment, stabilization system 120 is a programmable logic controller that contains a memory (not shown) for storing data transmitted by actuators 122, and a microprocessor (not shown) for processing the data to determine appropriate responsive actions to be taken. Such programmable logic controllers are well known in the art. Stabilization system 120 may then send commands to the actuators 122 and/or control valves 110 and 116 to take a predetermined action in response to the data received from actuators 122. For example, stabilization system 120 may automatically open or close either first control valve 110 or second control valve 116 to either start or stop the flow of micropellets from either the first or second micropellet sources, 102 and 104, respectively. In another embodiment, actuators 122 may be devices that contain appropriate elements/materials and circuitry that can be activated by stabilization system 120 to generate a magnetic field that affects the trajectory and/or speed of magnetized or metallic micropellets. As an example, actuators 122 may contain appropriate elements/materials and circuitry capable of producing physical vibrations at a desired frequency in order to facilitate the travel and separation of individual micropellets through the first and second conduits 108 and 114, respectively. Control valves 110, 116 and actuators 122 of the type described above are well known and, therefore, need not be further described herein.

In another embodiment, operation of control valves 110 and 116 and/or the actuators 122 may be controlled by computer 124 instead of stabilization system 120. In one embodiment, computer 124 is electronically coupled to actuators 122 and control valves 110 and 116 and controls their operation based on data and information received from stabilization system 120, pursuant to a protocol or program executed by computer. In yet another embodiment, computer 124 sends commands to stabilization system 120 which in turn relays those commands to the appropriate devices (e.g., actuators 122 or control valves 110, 116). It will be appreciated that any combination of elements such as sensors, actuators, processors, or controllers, or any other suitable

component may be used as part of a detector system. It will further be appreciated that these detector systems may not only be used to monitor micropellet microtargets, but also with any type of microtarget contemplated within the present invention.

In the embodiment shown in FIG. 1, when a micropellet 101 enters radiation chamber 118, it passes through the beam path of a low-power laser 126. A laser-beam-receiving circuit 128 ("receiving circuit 128") is also contained within radiation chamber 118 and positioned to be in the beam path of low-power laser 126. When the micropellet passes through the beam path of the low-power laser 126, it disrupts the laser beam that is fired by the low-power laser 126 and received by the receiving circuit 128. This disruption in the low-power laser beam is detected by the receiving circuit 128 which then sends a trigger signal to the computer 124 indicating that the micropellet has just passed a certain location within the radiation chamber 118. It will be appreciated that other motion detecting devices known in the art may also be used. For example, receiving circuit 128 may be a photodiode array or a charge-coupled-device (CCD) camera that detects either the presence or absence of light. Such devices are well known and commercially available.

In this example, upon receiving a trigger signal from receiving circuit 128, indicating that a micropellet has entered radiation chamber 118, computer 124 activates a firing device. For example, external trigger 130 is preferably coupled to a high-power laser 132 that will generate a high-energy laser pulse 134 when triggered by external trigger 130. External trigger 130 may be any circuit known in the art that is capable of triggering an energy source 132.

The high-power laser 132 in this embodiment can fire within a very short time (e.g., a few nanoseconds) after being activated by external trigger 130. Preferably, a detector system composed of several receiving circuits 128 and low-power lasers 126 can be utilized to give a more accurate calculation of the micropellet trajectory and speed. For example, multiple pairs of low-power lasers 126 and receiving circuits 128 can be strategically located at different positions and angles within radiation chamber 118 to more accurately determine the speed and trajectory of each micropellet as it travels through the radiation chamber 118 to reach the microtarget focal point of high-power laser 132. A low-power laser 126 in combination with a receiving circuit 128 is referred to herein as a "triggering circuit." By placing multiple triggering circuits at predetermined distances and angles from one another in the radiation chamber 118, micropellet speed and trajectory can be calculated by noting the points in time when

the micropellet passes through the beam path of each triggering circuit. It will be appreciated that triggering circuits may be configured in any suitable fashion.

Preferably, computer 124 receives data from the receiving circuits 128 and/or the actuators 122 and computes the trajectory, speed and repetition rates of the micropellets and provides a command signal to the external trigger 130 to fire the high-power laser 132. Computer 124 also sends feed back signals and/or command signals to the actuators 122 and control valves 110, 116, in order to control their operation and control the flow of micropellets into the radiation chamber 118. For example, by determining the speed and trajectory of a micropellet as it enters and travels through radiation chamber 118, the time required for the micropellet to reach irradiation area 117 can be calculated by computer 124. High-power laser 132 can then be activated to fire its laser pulse 134 within a few nanoseconds of the calculated time.

Additionally it is preferred that once the repetition rate, speed and trajectory of the micropellets have been stabilized, the laser in apparatus 100 can be focused on the micropellets in the required position at the beginning and will stay relatively focused from that point forward. For example, in apparatus 100, when variation in the laser focal spot is less than $\pm$ 5 μm along the laser axis and no more than $\pm$ 10 μm perpendicular to the laser axis, further laser focusing requires only minor adjustments due to minor variances in either the repetition rates, speed and/or trajectory of the micropellets. Desirably, to further compensate for any trajectory variation, the laser may be focused close to the micropellet insertion point.

While the preferred embodiments shown in FIGS. 1-5 utilize a high power laser 132, any energy source capable of discharging an appropriate energy beam into the irradiation area is contemplated within the present invention. For example, a table-top accelerator or synchrotron may discharge particles of the appropriate energy that will induce radiation of the desired wavelength upon irradiating a microtarget. Similar devices producing electron beams, proton beams, as well as light sources such as lasers, or any other appropriate energy source, may also be used. In a preferred embodiment, the present invention is illustrated using an electron beam as the energy source and will be described in detail with reference to FIG. 8.

Preferably, the energy source(s) direct an energy beam into the irradiation area along an energy path. Ultimately, some portion of the energy beam intersects with a

microtarget dispensed from the dispensing apparatus in the irradiation area, thereby emitting the desired radiation from the microtarget.

In apparatus 100, when high-power laser pulse 134 strikes an individual microtarget 101, the surface of the microtarget typically heats to a temperature sufficiently high to generate a plasma, such as temperatures of 0.1 million to 10 million degrees Kelvin (although any plasma generating temperatures may be selected). At such high temperatures, the microtarget becomes a plasma 135 and emits radiation in the desired spectral region. Desired radiation emissions, indicated by arrows 136, can be enhanced by choosing as the microtarget a solid material with emissions predominantly in the desired wavelength or spectral region.

The intensity and power of energy source 132 can be at any level required to achieve a radiation emission at the desired energy or wavelength from the irradiated microtarget. In a preferred embodiment, high-power laser pulse 134 can have power intensities on the order of $10^{11} - 10^{19}$ W/cm^2. However, it is understood that the present invention can utilize energy pulses of any power intensity and any duration, including a constant energy beam, that is either lower or higher than the ranges specified herein. For example, when ~1.2 keV x-rays are desired, Cu micropellets may be irradiated with a laser pulse intensity of 10^{14} W/cm^2. In another application, if ~8 keV x-rays are desired, Cu micropellets may be irradiated with a laser intensity of 10^{19} W/cm^2, or higher. In a further application, if 90 eV (13 nm) EUV radiation is desired, Sn micropellets may be irradiated with a laser intensity on the order of 10^{12} W/cm^2.

The conversion efficiency may be enhanced by irradiating the microtarget with more than one energy pulse. In one embodiment, energy source 132 includes a laser (or multiple lasers) providing a low energy laser pre-pulse that first generates a "cold" plasma from a microtarget and subsequently "heats up" the generated plasma with a second laser pulse (either from the same laser or a different laser), which ultimately emits the desired radiation. In generating the cold plasma, the low energy laser irradiates the microtarget with a pre-pulse preferably having an energy of a few millijoules and short pulse times of 10 fs-10 ps. However, it will be appreciated that the pre-pulse may have any energy intensity that creates a plasma upon irradiation of the microtarget, but typically approximates $I_L \sim 10^{11}$ W/cm^3. The pre-pulse may be generated by the same laser that generates the subsequent high energy pulse, although multiple lasers may also be used.

In this embodiment, the second high energy laser pulse irradiates the plasma that is pre-formed with a low energy pulse. Preferably, the delay between the pre-pulse and the high energy pulse is chosen to maximize optimum density conditions ("the critical density") for the plasma to efficiently absorb the main laser pulse, and converting the maximum amount of desired radiation from the plasma. Typically, the critical density of a plasma irradiated by a ND-YAG laser is lower than the density of a given material in the liquid or solid state by approximately a factor of 100. During the delay between the pre-pulse and the high energy pulse, the plasma density decreases via plasma expansion, and preferably reaches critical density at the time the high energy pulse irradiates the plasma. The delay between the two laser pulses preferably is in the range of 100 ps - 1 ns, although any other delays between pulses that ultimately result in emission of the desired radiation from the plasma may also be used.

The intensity, I_L, of the high energy pulse should be high enough to heat up the pre-formed plasma to a temperature that will emit the desired radiation. For example, in order to induce an L-shell emission in copper, the high energy laser pulse should have sufficient energy to raise the plasma temperature high enough to ionize copper atom to the Cu^{+19} state. These temperatures typically vary according to the type of solid material, the size of the microtarget, the size of the plasma, and the type of emission desired, among other factors.

Pre-forming a plasma can be used to enhance the energy conversion efficiency of the plasma in that plasma density and pressure are adjusted as desired using delay between laser pulses, the energies of the laser pulses. Moreover, the density and pressure an be tailored as desired to generate a particular radiation emission, as readily will be appreciated by one skilled in the art. In addition, a pre-formed plasma used in the preferred embodiment generates a more uniformly emitted radiation emission. As a result, positioning of radiation collection devices within the radiation chamber may be positioned to optimize the amount of radiation collected. For example, mirrors collecting EUV radiation may be positioned at desired locations to optimize the amount of radiation collected, or a larger collection angle may be used than is possible using a single laser pulse. Yet another advantage stems from the ability to ionize the entire microtarget using a multi-pulse system that may not be possible using a single pulse system, leaving no neutral target mass. When the microtarget is completely ionized, the resulting target debris is also completely ionic.

This creates an advantage in that ionic debris is much more easily deflected or controlled than neutral debris. For example, electromagnetic fields may be optimally positioned and used to deflect and control the resulting ionic debris away from equipment associated with the laser and radiation beamline. Additionally, because the plasma generated by the pre-pulse will expand to the required diameter for the high energy pulse, much smaller microtarget masses are possible using a pre-formed plasma, and as a result, much less debris is generated from each microtarget.

Solid micropellets are generally commercially available in sizes of 36 – 75 microns in diameter or higher, roughly approximating the grain size of medium to fine powders. Micropellets of this size are reasonably well matched to a laser focal spot diameter of 10 microns and the laser ablation depth of less than 1 micron from the microtarget surface of the system, as in the disclosed example.. However, smaller size micropellets of 10 microns or less may be used for certain laser irradiation conditions such as pre-formed plasma conditions, or to minimize target debris even further. Larger or smaller micropellets may be used depending on the specific application taking into account the energy source, the system configuration, and the focal spot diameter.

Preferably, a collector arrangement 138 collects the microtargets once the microtargets have passed through the irradiation area. For example, in one embodiment illustrated in FIG. 1, after each micropellet is irradiated with a high-power laser pulse 134, a majority of its mass remains and falls into a the collector arrangement 138, which is illustrated as collection bin 138. As shown in the embodiment illustrated in FIG. 1, collection bin 138 preferably includes a funnel intake 140 for catching the remaining mass of the micropellet targets after they have been hit by the laser pulse 134. Funnel intake 140 then funnels the microtarget remains into the collection bin 138. The configuration of the funnel intake 140 facilitates the capture of the micropellets while preventing the micropellets from spilling out of collector 138. Preferably, an unused target bin 139 is positioned directly below gun apparatus 112 such that unused micropellets will drop unaided into unused target bin 139. In operation, the micropellets 101 in bin 139 may be reused for further radiation generation by reinserting the micropellets into source bins 102 or 104.

The use of microtargets 101 substantially reduces ion ablation when compared to other types of solid targets (e.g., solid blocks or thin tape). In one embodiment of

apparatus 100, when laser pulse 134 strikes a micropellet 101, a hot plasma 135 forms on its surface. The remaining micropellet mass is propelled backward by the reaction force of the material ablated by the laser pulse 134 and falls into collection bin 138. Typically, the formation of the plasma results in an ablation depth of approximately one micron into the surface of the micropellet, as described above. Since the remaining mass of the micropellet is neatly discarded in bin 138 after it has been irradiated, clean up and maintenance costs of the system equipment are significantly reduced. It will be appreciated that bins 138, 139, and funnel 140 may be configured in any shape and positioned in any location that facilitates collection of microtargets once they have been dispensed from dispensing apparatus and passed through the irradiation area. It will further be appreciated that as a further advantage, the micropellets collected in bin 139 offer a recyclable source of microtargets currently unavailable in existing solid target systems.

To further reduce or eliminate the contaminating effects of ion ablation, apparatus 100 illustrates one embodiment of a debris removal arrangement for substantially preventing target debris from contaminating system equipment. Preferably, the debris removal arrangement is in communication with the irradiation zone 117, the energy path from laser 132 to the irradiation zone, and beamline 142, in order to effectively prevent target debris such as ablated ions generated in the irradiation zone from contaminating equipment associated with the laser or any other appropriate energy source or equipment associated with the beamline. It will be appreciated that the debris removal arrangement may include any device that prevents target debris from reaching equipment associated with the energy source or beamline without substantially inhibiting the direction of the desired radiation into the beamline.

In the disclosed example shown in apparatus 100, the debris removal arrangement incorporates a circulation system 151, including circulation conduit 146, a circulation pump 152 and filter 154. Circulation conduit 146 has a first open end 148 for the intake of air or gas within chamber 118 and a second open end 150 for the outtake of air or gas within the chamber. Preferably, circulation pump 152 pulls gas into the intake 148 of conduit 146 and thereafter expels gas out of the outtake 150. The gas expelled from outtake 150 is directed toward the energy path of laser pulse 134 and beamline 142 such that the gas flow will direct ablated ion contamination away from beamline 142 and laser lens 133.

Preferably, the debris removal arrangement includes a filter 154 for filtering the gas as it passes through circulation conduit 146 to remove impurities and contaminants produced from the plasma resulting from irradiating the micropellet target. In one embodiment, the gas in the radiation chamber 118 is helium gas, pressurized at any desired pressure that allows for radiation transmission. As helium is circulated and filtered by the circulation system 151 described above, the helium substantially prevents ablated ions and other target debris from entering beamline 142 but does not block radiation emissions from entering beamline 142. Helium ions collide with ablated ions before target debris can come in contact with expensive system equipment. Preferably, the gas is expelled from outtake 150 of circulation conduit 146 toward radiation area 117, and collides with ablated ions. The gas and target debris travel through intake 148 where filter 154 filters out contaminating target debris before the gas is recirculated by pump 152. In this way, a significant amount of target debris is diverted away from beamline 142. In a preferred embodiment in which system 100 generates x-rays, helium (He) gas passes through circulation system 151. Because helium is transparent to x-ray emission, x-rays are received in beamline 142 while target debris is stopped before reaching beamline 142. The use of helium gas to remove target debris such as ablated ions while transmitting x-ray emissions is well known in the art.

Adjacent to the irradiation area, beamline 142 receives radiation generated by the irradiated microtargets and directs the radiation to a desired exposure area where objects to be exposed to the generated radiation may be positioned. For example, when EUV radiation is generated, silicon wafers positioned in the exposure area may now be etched with the generated radiation for lithography purposes. It will be appreciated that any type of device used to receive, direct, focus, detect, or otherwise process the radiation emitted from the microtarget may be contained within beamline 142. Any combination of these devices is also contemplated within the present invention. For example, in a preferred embodiment, beamline 142 includes a radiation processing device 144 which may contain filters, collimators, shutters, and other optics (e.g., mirrors, lenses, gratings etc.) to further filter and shape the radiation delivered to the object placed in the exposure area. Such radiation processing devices are well known and commercially available.

In one aspect of the invention, when a microtarget emits radiation at more than one desired wavelength, the apparatus of the present invention can generate radiation

at different wavelengths without reconfiguring the system. For example, laser intensities of $I_L \sim 10^{15}$ W/cm^2 induce L-shell emissions of ~4 keV from tin (Sn). Lower laser intensities of $I_L \sim 10^{12}$ W/cm^2 induce Li-like ion emissions of ~0.1 keV (EUV radiation) from the same tin microtarget. By adjusting existing filters in beamline 142 and adjusting the laser power, preferably by computer 124, two different types of radiation are generated from the same microtarget without system reconfiguration. Similarly, Ga emits soft x-rays (~0.3 keV), hard x-rays (~10 keV), and VUV radiation (~54 eV) when irradiated by an appropriate energy source. In the same manner, In emits EUV radiation (~0.1 keV), x-rays (~4 keV), and hard x-rays (~29 keV) without the need for extensive system reconfiguration. It should be appreciated that these are examples only and other configurations may be used to generate other desired emissions.

The use of solid micropellets as microtargets, in accordance with the invention, substantially eliminates the disadvantages associated with gases, liquids, frozen liquids, or other types of solids as utilized in existing methods and systems. The solid micropellets are significantly easier to handle and store. Additionally, as described above, multiple bins of various types of micropellet materials can be implemented in a single system so as to provide a system that can easily and quickly produce a large variety of energies of different wavelengths. Such a system cannot be easily implemented when using liquids or gases because conduits to the radiation chamber are specifically configured for the particular substance to be used. Advantageously, since the use of solid micropellets does not require a vacuum within chamber 118 as does existing liquid systems the cost and size of the chamber is further reduced. The relatively compact space needed for the present invention creates advantages over thin tape target systems that need much more instrument space and cannot currently operate continuously beyond a few days.

FIG. 2 illustrates another preferred embodiment in which the solid target material selected to form the microtarget 210 is melted, prior to irradiation, into liquid form. Advantageously, the resulting surface tension of the liquid creates a nearly perfect spherically shaped microtarget for irradiation. As noted earlier, a uniform shape substantially increases the accuracy in positioning the energy source and calculating the trajectories of target debris and radiation emission. As microtargets may be formed from any material that emits the desired wavelengths, preferably a

solid at room temperature, this preferred embodiment provides the known benefits of both liquid and solid materials.

It is also desirable to select a solid material with a relatively low melting point. Advantageously, solid materials such as Ga, In, and Sn have low melting points and are desirable microtarget materials. However, materials with higher melting points, such as Cu, may also be used. Some alloys such as tin solder and brass have lower melting points than their respective components and also are desirable microtarget materials. For example, brass, composed of copper and zinc, has a lower melting point than either copper or zinc. Choosing solid materials with relatively low melting points decrease the energy costs associated with using a liquid-formed microtarget.

Apparatus 200 further includes a solder jet assembly as the dispensing apparatus 228. In this embodiment, the solder jet assembly incorporates a heating reservoir 222 connected to a dispensing nozzle 226. In one example, the solder jet assembly dispenses volumetric amounts of liquid with a droplet diameter in the range of 25 - 125 μm a rate up to 1000 droplets per second. Such an assembly allows for volumetric droplet formation on demand through piezoelectric vibration or heat induction. In the illustrated example, the solder jet assembly (illustrated with number 228) dispenses through a single nozzle 226, although typical commercially available solder jet assemblies have multiple nozzles. In another embodiment, the dispensing apparatus 228 comprises other liquid droplet dispensing or injecting apparatus, such as one or more ink jet assemblies, such as known in the art.

Preferably, solid target material 224 is heated to a molten liquid state in reservoir 222. It will be appreciated that target material 224 may optionally be converted to its liquid state before placement in reservoir 222, with the reservoir preferably maintaining the material in a liquid state. For example, heating element 229 converts and/or maintains target material 224 in a liquid state. Any form of heat source or arrangement may be used that can maintain the liquid state of the target material 224.

It will further be appreciated that more than one type of solid or solid alloy may also be placed in the reservoir 222 and serve as the target material. For example, microtargets formed from brass present additional advantages. In one preferred embodiment, generating x-rays from a brass microtarget 210 results in both copper and zinc emission lines. Harvesting the summation of these emission lines increases

the efficiency of the radiation generation process. As an added benefit, brass has a lower melting point than either copper or zinc alone, thereby decreasing the energy costs of the system.

Referring again to FIG. 2, in operation, target material 224 travels from reservoir 222 through dispensing nozzle 226 of a dispensing assembly 228 (i.e. solder jet assembly in the illustrated embodiment). Preferably, piezoelectric vibrators 220 are positioned adjacent to nozzle 226 and help induce spherical formation of the target material into microtarget droplet 210. Piezo-vibration also regulates microtarget delivery into irradiation area 117 at consistent micro- or nanosecond intervals. The laser repetition rate can be synchronized to the microtarget delivery rates for optimizing the accuracy and timing of irradiation by the laser 132 in irradiation area 117. Chemical properties of the selected solid material determine whether the microtarget is in liquid or solid form when the microtarget reaches the irradiation area and is irradiated by the energy source.

Once microtarget droplet 210 is dispensed, gravity and a dispensing force directs the droplet into irradiation area 117. Alternatively, a gas compressor 227 delivers the microtargets into irradiation area 117 at an accelerated rate. A low-power laser 126 and receiving circuit 128 is positioned to monitor the target path of target droplet 210, and triggers a high energy laser pulse 134. However, other detecting devices known in the art may be coupled to the energy source in order to effectively coordinate irradiation of the microtarget by the energy source in the irradiation area.

For example, FIG. 3 illustrates an apparatus 300 with sensor(s) 310 located in the beamline 142, as is the preferred embodiment. As with all communication connections in the present invention, wired, or wireless connections may be used between sensor 310 and the controller, which is illustrated as computer 124. As described with reference to FIG. 2, computer 124 is connected to external trigger 130, which is connected to the high power laser 132 being used as the energy source. The sensor monitors the intensity of x-ray emissions, i.e., the quantity of x-rays being emitted from the microtarget and focused into beamline 142. By coupling the sensor 310 to computer 124, the timing of external trigger 130 may be adjusted to maximize the intensity of x-ray emissions received in beamline 142. Sensors of this type are well known in the art.

Debris can be reduced through the use of electromagnetic fields (or other techniques) to deflect or repel charged particles ejected from the microtarget during

operation. For example, in the embodiment illustrated in FIG. 2, a magnetic field is generated between poles 216 in order to deflect any target debris that may damage the laser lens 133, laser system, or radiation beam line filters or mirrors contained in radiation processing device 144 in beamline 142. The poles 216 preferably are placed on either side of the droplet trajectory at the point of laser irradiation. Since the microtarget consists of charged particles, the magnetic field deflects target debris particles emanating from the target droplet. By constructing an electric field between electrodes 218, preferably positioned between irradiation area 117 and the x-ray processing device 144, ionized ablated ions are deflected and prevented from entering beamline 142.

Additional debris direction can be achieved using a temperature gradient. In one preferred embodiment of generating a temperature gradient, cold finger 214 and hot finger 212 are positioned in x-ray chamber 118 generating a temperature gradient between them directing the lased microtarget droplet target debris towards the cold finger. Alternatively, the cold finger 214 may be used alone, without the use of hot finger 212. When exposed to the colder temperature zone, the microtarget droplet will condense to the solid state for easier disposal or recycling.

In one embodiment, debris is also removed by directing a helium stream, such as from jet 230, away from laser lens 133 and/or beamline 142. It will be appreciated any other suitable gas may be used to sweep target debris away from the laser lens or beamline. For example, hydrogen or krypton may be used. In another preferred embodiment a thin window 232 is positioned between irradiation area 117 and x-ray processing device 144. For example, the thin window may be a 0.2 μm thick beryllium (Be) foil.

It will readily be appreciated that any combination of these elements or any other apparatus for avoiding contamination from ablated ions may be incorporated in a debris removal arrangement. In addition, any other suitable detecting devices may be coupled to the energy source in order to effectively coordinate irradiation of the microtarget by the energy source in the irradiation area.

The debris removal apparatus alternatively (or additionally) may include a supersonic jet system 400, as illustrated in the alternative embodiment illustrated in FIG. 4. In this embodiment, gas flows through a gas circulation conduit 418. The gas selected preferably allows transmission of radiation with minimal absorption. For

example, hydrogen (H_2), helium (He), and krypton (Kr) gases are generally transparent to EUV radiation when the gas pressure is low enough, e.g. typically less than 1 torr. and accordingly are suitable examples of a gas used in conduit 418 when it is desired to use the apparatus of the present invention for the generation of EUV radiation. Conduit 418 is connected to a converging-diverging supersonic nozzle 421 with a sonic throat at 420. The gas expands in diverging portion 422 of nozzle 421, preferably resulting in supersonic velocity at static pressure, P_1, in region 423. Preferably, P_1 matches the gas pressure of chamber 118. For example, in an example of this arrangement (using He gas in an EUV radiation generating system), if the desired pressure at the exit nozzle 422 equals 1 torr (P_1), and the conduit pressure at P_0 in conduit region 419 equals 1000 torr, a supersonic Mach 6.6 nozzle will produce a desired 1 torr pressure at the nozzle exit. The He pressure in region 423 preferably remains at 1 torr, so as not to absorb the desired EUV radiation. Furthermore, the supersonic velocities of the gas can act to efficiently sweep target debris away from equipment associated with the laser 132 and beamline 142. It should readily be appreciated that other gases and supersonic nozzle designs may be used, which will create correspondingly different pressures and gas velocities. Preferably, supersonic nozzle designs may be optimized for a specific application. It will be appreciated that any number of factors may be considered in optimizing the nozzle design, such as the configuration of radiation chamber 118, the type and size of the microtarget, the size of the nozzle, the gas selected, and the desired radiation wavelength, among others.

In one embodiment, the supersonic gas emerging from portion 422 is at static pressure P_1, in region 423 and that pressure is preferably equal or higher than the pressure of the surrounding gas in radiation chamber 118 (not shown). In this embodiment, the irradiation area is located in region 423. The energy source and resulting energy beam irradiate the microtarget, producing a plasma that generates the desired radiation. Target debris preferably is entrained by the supersonic flow into the supersonic diffuser portion 430 of conduit 418.

In the illustrated example, as the supersonic gas and debris swept away by the gas pass through supersonic diffuser 430, the gas becomes subsonic through a series of shock waves, resulting in an increase in static pressure at P_2 in region 431. In one example, helium (He) gas is used and travels through region 423 at Mach 6.6 (with the concomitant pressures in regions 419 and 423 as described earlier), the static pressure increases from P_1 to P_2 by a factor of fifty or more. Preferably, the subsonic

gas is recirculated through filter 154 and pumped back to supersonic nozzle 421 at pressure P_0.

These differing pressure regions P_0, P_1, and P_2, enable supersonic gas speeds while advantageously creating a region 423 that effectively transmits the desired radiation. For example, in one embodiment, Sn microtargets 210 are irradiated by a high power laser 132 configured to emit EUV radiation utilizing He gas in system 400. He gas transmits EUV radiation at relatively low pressure ($P \lesssim 1$ torr), but absorbs EUV radiation at higher pressures. In this example, conduit 418 is shaped and configured such that the pressure at a top section of the conduit 418 is $P_0 = 1000$ torr, between the top open portion 422 and the diffuser 430 is $P_1 = 1$ torr, and the pressure in the bottom section of the conduit 418 is $P_2 = 100$ torr. Mach 6.6 supersonic nozzle 420 produces the pressure in irradiation area 117 (not shown) between the top open portion 422 and the diffuser 430. It will be appreciated that other configurations creating the requisite pressure differentials are also contemplated within the present invention.

In the illustrated embodiment, the high velocity gas sweeps target debris such as ablated ions away from equipment associated with the energy source or beamline. In this manner, the supersonic jet system 400 can serve to prolong the life of the system equipment by decreasing target debris contamination.

In addition, the insertion of microtargets at supersonic speeds significantly enhances the radiation generation efficiency over relatively static systems. For example, the present invention may be employed to generate EUV radiation for EUV lithography applications, such as the etching of sub-100 nm microcircuits. By practicing the present invention using, for example, tin as the microtarget in micropellet form, the EUV conversion factor may be up to ten times higher than that of other targets, such as water or xenon. For example, usable EUV emission for EUV lithography application reside in a 2.5% bandwidth between 13 - 14 nm (~89-95 eV) based on the construction of the radiation absorbing mirrors 558. Unfortunately, systems using Xenon (gas or liquid) or water targets only have limited line emissions in this spectral region and the spectral lines have a much narrower bandwidth acceptance, typically about 0.1%. Thus, much of the available bandwidth is not being used. By contrast, the present invention may use solid materials having a wider bandwidth acceptance. For example, a tin microtarget has a bandwidth much wider than 2.5%, and correspondingly, mirrors 558 can collect more of the generated

radiation. Because the intensity of tin's line emissions in the 2.5% bandwidth between 13 nm and 14 nm are so much higher, the conversion efficiency for tin may be up to ten times higher than for existing xenon or water systems.

In another embodiment, the microtargets are molten Sn liquid droplets. Practitioners in the art will understand that any liquid or solid microtarget may be used with the supersonic jet system. Additionally, the supersonic jet system may also be utilized in current liquid systems as well. Hence, the supersonic jet system as described above represents a significant advance in the field of EUV lithography.

Another advantage of supersonic jet system 400 stems from its ability to optionally provide differential pressure regions. In the preferred embodiment generating EUV radiation shown in FIG. 5, a large collection solid angle EUV source with supersonic gas flow with low radiation absorption (e.g., H_2, He, or Kr) highlights an additional feature of source generation in creating a higher pressure region that is adjacent to a lower pressure region. Preferably, laser beam 132 is focused by lens 133 onto microtarget 510 in irradiation area 117. Optionally, laser 132 may be, for example, a singular annular laser beam or one or several circular laser beams using multiple focusing lenses. In one embodiment, on or more lenses 133 are positioned around conduit 416 and focus laser beams 134 on microtarget 510 in irradiation area 117. Multiple lasers may be configured to fire laser pulses simultaneously, resulting in a single, coincident irradiation of the microtarget. Alternatively, the lasers may be timed to fire sequentially. Advantageously, sequential firing of multiple lasers result in rapidly pulsed irradiation approaching a continuous beam of laser energy. Timed to the delivery of the microtarget into irradiation area 117, a pulsed energy beam approaching continuity represents a significant advance in efficiency by markedly increasing the rate of irradiation. Practitioners in the art will understand that any configuration of an energy source that intersects an energy beam with a microtarget in the irradiation area is contemplated within the present invention.

One illustrative embodiment of the supersonic flow system is provided in FIG. 5. Flow element, blunt body duct 524, is centrally located in diffuser 430. The supersonic gas flow impinging on duct 524 will generate a standing shock wave 526 (shown by dashed lines), creating a higher pressure region 528 within wave 526 and a lower pressure region 530 outside shock wave 526. Preferably, region 528 exists generally from the edge nearest the microtarget of blunt body duct 524 and extends to shock wave 526. This phenomenon in well known in the fluid mechanics art.

Dispensing apparatus 506 delivers a microtarget toward the center of duct 524. Preferably, microtarget delivery and laser pulsing are synchronized such that the point of irradiation and the resulting laser plasma occurs within blunt body duct 524, close to the boundary of, but within shock wave 526. Because the gas pressure in region 528 is relatively high, absorption of EUV radiation is correspondingly high in this region. Desirably, the distance from the initial plasma to the shock wave 526 is small, preferably a few millimeters or less. As such, the desired radiation will propagate through only a few millimeters of higher pressure gas with some absorption occurring in this area, pass through shock wave 526, and into lower pressure region 530, and then propagate over a much longer path in lower pressure region 530 toward reflecting mirrors 557 with much less absorption. In this manner, target debris such as ablated ions generated during irradiation of the microtarget are substantially stopped within the higher pressure zone and swept away through duct 524 and into diffuser 430 and into conduit region 431 by supersonic jet system 400. It should be appreciated that the geometries of shock wave 526, and correspondingly, higher pressure region 528 and lower pressure region 530 will vary according to system configuration.

In this embodiment, beamline 142 is generally comprised of mirror 557, window 558, and radiation processing equipment 144 (not shown). Mirror 557 reflects and directs EUV radiation 136 generated by the laser plasma toward window 558, where the radiation is received and processed by radiation processing equipment 144. In this embodiment, window 558 may be any EUV absorbing surface. For example, 0.2 μm Be or 0.2 μm Si foils may be employed as windows. In typical lithography applications, once the generated EUV radiation is collected by window 558, processing equipment 144 may include further collection or shaping optics which illuminate an EUV mask, followed by EUV projection mirrors which print the mask features on a photoresist on silicon wafers exposed to the EUV radiation generated in irradiation area 117. Practitioners in the art will understand that any configuration of radiation processing equipment 142 is contemplated that will direct and prepare the radiation received in beamline 142 for ultimate use.

The large solid angle collection (approaching 2 π) of the desired radiation increases the collection efficiency of EUV radiation and also minimizes absorption near jet nozzle 420 as well as minimizing target debris. Additionally, the present

invention allows for substantially more compact configurations also unavailable in current systems, e.g., systems using thin tape targets, and thus providing systems that may be utilized in smaller spaces.

The embodiment illustrated in FIG. 7 highlights yet another advantage of the present invention. Conduit loop 518 illustrated in FIG. 7 is completely enclosed and sealed from the external radiation chamber 118, thereby creating a closed loop circulation system that optionally may also employ a supersonic jet system. For example, in the particular example disclosed in FIG. 7, microtarget apparatus 506 extends through gas conduit loop 518. Gas conduit loop 518 operates substantially similar to conduit 418 employing an open loop system. The end of apparatus 506 is positioned very near nozzle 520. As each microtarget travels down apparatus 506 toward the irradiation area, the microtarget is advantageously pulled out (or entrained) from apparatus 206 by a vacuum created by the gas travelling at high velocity past the bottom opening of apparatus 206. In this manner, each microtarget is propelled at very high speeds into irradiation area 117. As this embodiment is a closed loop system, the high speeds attained by the gas are maximized for more faster microtarget delivery as well as more efficient target debris removal. It will be appreciated that apparatus 700, including the insertion of 506 into conduit loop 518, may be used with any dispensing system of the present invention, such as for delivering either liquid or solid microtargets, and combined with any other debris removal elements.

Preferably, conduit loop 518 further includes a conical and cylindrical wall 556 that extends outwardly from the irradiation area. In this disclosed example, the open end of the cylindrical wall 556 mates with the laser lens 133 to provide a sealed enclosure between the cylindrical wall 556 and lens 133. In this way, there are no gaps or openings within the system 700. The cylindrical wall 556 surrounds a laser path for the laser beam pulse 134 emanating from the laser lens 133. Thus the wall 556 allows the conduit loop 518 to remain completely enclosed while also allowing laser beam pulses 134 from an external laser source to enter the enclosure.

In the embodiment illustrated in FIG. 7, examples of suitable microtargets include microtargets including one or more of the following elements: tin, indium, stibium, gold, or lithium, although of course any suitable radiation emitting material may be used. The microtargets are irradiated by laser beam pulse 134, generating a plasma 135 and emitting EUV radiation 136. The EUV radiation 136 travels through an EUV window 558 along beamline 142 and through radiation processing devices

144, for example, a series of optical filters. In one embodiment, EUV window 558 is a 0.2 micrometer thick Beryllium window. In another embodiment, EUV window 558 may be a 0.2 micrometer thick Silicon window.

FIG. 8 illustrates an embodiment of radiation generation system 800 using an electron beam as an energy source for irradiating microtarget 210. In one illustrated example, a solid material is maintained in molten state in sealed reservoir 222 and under pressure from recirculation pump 830. Preferably an ink jet-type nozzle 226 dispenses microtarget droplet 210 into radiation chamber 118, which is optionally under vacuum 820. Optionally, piezoelectric vibrators 220 vibrate nozzle 226, thereby regulating microtarget 210 delivery at consistent intervals, preferably around 10^6 droplets per second (~ 1 MHz repetition rate). Advantageously, nozzle 220 also sends microtargets 210 on a substantially stable trajectory, preferably, within +/- 5 μm at a distance of 5 - 10 mm from nozzle 226. Preferably, the microdroplet diameter is 10 - 100 μm, but other diameters may be used depending on the desired radiation source size and the power emitted from the electron beam, among other factors.

In the embodiment illustrated in FIG. 8, power supply 832 creates an electron beam 834, which is focused by an electromagnetic lens system 833 that focuses electron beam 834 on the microtarget in irradiation area 117. Ground 831 grounds power supply 832. In this example, irradiation by electron beam 834 generates x-ray radiation 136. Of course, other desired wavelengths may be generated, and other optical and electrical configurations of the electron beam and lens system may be used. For example, magnets 834 may be used to focus the electron beam.

Preferably, electron beam 834 delivers 100ns pulses, however, other pulse durations may be employed that deliver the requisite energy to emit the desired radiation. For example, at least 30 keV electron beam is needed to produce K-shell emissions of ~10 keV from Gallium (Ga). The maximum energy of the electron pulse is limited by the heat of vaporization of the microtarget. If the microtarget is vaporized, the resulting vapor may obstruct the propagation of the electron beam. Nevertheless, a debris control system employing, for example, a high volume vacuum pump, cold finger, temperature gradient, or electromagnetic fields may be used to substantially eliminate vaporized material from the path of electron beam 834. As an example, when x-rays are generated using system 800 and a debris removal arrangement employed such that vaporized target material is eliminated from the

beam path, the electron beam intensity may be increased by a factor of five because of the higher energy deposited into the microtarget, and allowing for some vaporization. For example, in one embodiment using Ga microtargets, an excess of 2 kW of electrical power may be deposited on Ga microtargets if the target is not vaporized. By contrast, when some target vaporization is allowed, based on the benefits of using a debris removal arrangement, an excess of 10 kW may be deposited on the Ga microtargets.

X-ray source size preferably is relatively small, preferably 20 - 100 μm. System 800 presents other advantages over existing rotating anode systems in that these prior systems are expensive to maintain, requiring teams of highly trained individuals to monitor and care for the rotating anode. For example, because rotating anode sources are not sealed tubes, rotating anode sources require a vacuum pump, and associated maintenance requirements. Likewise, production costs are increased in prior systems because of the need to constantly cool the anode. By contrast, system 800 may be employed as a closed loop system, creating a sealed tube and obviating the need for an external vacuum pump 820.

Another advantage of system 800 stems from the highly desirable brightness of the generated source. For example, very bright x-ray sources, such as x-rays emitted from Cu microtargets, is desired for x-ray powder diffraction in semiconductor, chemical and pharmaceutical industries. Because of the brightness of the source, x-ray radiation, for example, may be collected very efficiently by an x-ray mirror 815. This mirror can either focus or collimate the x-rays out of x-ray chamber 118 through window 832. In one embodiment, mirror 815 may utilize paraboloid-shaped micromirrors obtained from Reflex, an associated company of Bede Scientific Instruments, Ltd., located at Bowburn South Industrial Estate, Bowburn, Durham, DH6 5AD, UK.

The geometry of system 800 also enables relatively close access to the radiation source. For example, x-ray mirror 832 may be placed very close, preferably 2-5 mm behind the microtarget. As a result, result, more radiation is efficiently collected and redirected into beamline 142, thereby increasing the brightness of the x-ray source. For example, x-rays generated using the present invention may be 10 times as bright as x-rays generated from a rotating anode source.

System 800 also provides a renewable source of microtargets. After passing through irradiation area 117, regardless of irradiation by the electron beam, microtargets 210 continue to fall into collector bin 839, which is grounded by ground 845. Ground 845 grounds the excess electric energy that is deposited on the microtargets during irradiation and is necessary when employing a closed loop system. In bin 839, the microtargets are reheated by heater 840, thereby converting or maintaining the microtargets in a liquid state. Recirculation pump 830 pumps the liquid material back to reservoir 222. Also, pump 830 provides the required pressure to reservoir 222 to dispense the microtargets 210 through nozzle 226. Beneficially, this process insures that the radiation chamber, for example, an x-ray tube, can be sealed, switched on or of on demand. More beneficially, only a short heating time is required when switching on the system before the steady flow of microtargets is generated.

A method for generating radiation of a desired wavelength from a microtarget is illustrated in FIG. 6. This method practiced according to one embodiment of the present invention is shown in block diagram 600. Block 610 selects a solid material that is suitable as a microtarget material. Critically, when irradiated by an appropriate energy source, the solid material emits radiation of a desired wavelength or energy. For example, when irradiated by a high power laser with laser intensities of $I_L \sim 10^{14}$ W/cm^2 Cu emits x-ray radiation of ~1.2 keV. It will be appreciated that the irradiated solid material may emit radiation of multiple wavelengths, or energies. For example, an energy source irradiating at $I \sim 10^{15}$ W/cm^2 will emit ~4 keV x-ray radiation from solid Sn. However, when irradiated with energies of $I \sim 10^{12}$ W/cm^2, Sn will emit ~0.1 keV EUV radiation. Desirably, the solid material is a solid at ambient temperature and pressure. Because the sheer variety of available solid materials suitable for generating radiation of a desired wavelength dwarfs the number of available liquids or gases that emit radiation in current systems, the present invention accords a number of advantages over these systems. For example, a larger variety of spectral wavelengths are now available by practicing the present invention that are not currently available under existing systems. As another advantage, the present invention enables a larger variety of materials to be used to generate radiation of a particular wavelength. For example, Be, Li, Cu, In, Sb and Sn, will typically all generate EUV radiation at ~0.1 keV (13 nm-14 nm wavelength). Depending, for example, on the cost or availability of the solid material, its melting point, toxicity,

the type of energy source being used, or the configuration of the system, one of these solid materials may be preferable over the others. In this manner, the present invention adds flexibility to current radiation generating systems that are limited by the dearth of available radiation generating materials.

Block 620 provides the solid material as a discrete microtarget. Desirably, the microtarget is of such a size that minimizes target debris and ion ablation. It will be appreciated that the microtarget may be provided as either a solid or a liquid. For example, solid micropellets, as described earlier along with the corresponding advantages, may be used. Alternatively, microtargets may be formed from blocks of solid material that have been melted into a liquid and then portions of this molten liquid may form liquid microtargets. For example, a solder jet assembly or other ink jet-type nozzles may be used to provide discrete liquid droplet microtargets. As another example, liquid microtargets may also be provided as a mist. It will be appreciated that other types of microtargets are contemplated within the present invention.

Block 630 delivers the microtarget into an irradiation area. In accordance with the present invention, the microtarget may be delivered using vacuum, compressed gas, gravity, supersonic gas, or any other delivery methods known in the art to deliver the microtarget into an irradiation area. Additionally, any of these methods may be combined to effect delivery. For example, in one embodiment, supersonic gas propels the microtarget into an irradiation area. Concurrently, the pressure differential that creates supersonic velocities also causes a concomitant vacuum at the end of the microtarget dispensing nozzle, thereby entraining the microtarget from the nozzle toward the irradiation area.

Block 640 irradiates the microtarget with an energy source along an energy path. Critically, the energy source must emit an energy beam of the appropriate energy such that irradiation of a microtarget by the energy beam produces radiation of the desired wavelength. For example, a high power laser emits an appropriate energy beam such that when a high power laser irradiates Cu with a laser pulse of $I_L \sim 10^{14}$ W/cm^2, L-shell emissions of ~1 keV are emitted from the Cu microtarget. Practitioners in the art will understand that any other energy source that will emit the desired radiation from a microtarget may be used. For example, electron, proton, or other particle beams, or other laser configurations are contemplated within the present invention.

Block 650 directs the desired radiation emitted from the microtarget along a beamline path from the irradiation area into a beamline. Preferably, radiation may be directed, for example, using mirrors, windows, and judicious placement of the beamline within the radiation generating system. The beamline may be placed in any location that receives or is exposed to the desired radiation, although it is desirable to position the beamline in a location that maximizes collection of radiation of the desired wavelength while minimizing target debris and extraneous emissions of undesirable wavelengths.

Block 660 substantially removes target debris from the energy path and the beamline path such that target debris and other pollutants do not come in contact with system equipment such as equipment associated with the energy source and beamline. For example, a debris removal arrangement, configured with various elements described earlier in many different embodiments, may be used to stop and remove target debris.

One skilled in the art will appreciate that the present invention can be practiced by other than the preferred embodiments which are presented in this description for purposes of illustration and not of limitation, and the present invention is limited only by the claims which follow. It is noted that equivalents for the particular embodiments discussed in this description may practice the invention as well.

WHAT IS CLAIMED IS:

1. A radiation generating system using a microtarget including a solid material, comprising:

a dispensing apparatus dispensing a microtarget on a microtarget path;

an energy source, emitting an energy beam along an energy path;

an irradiation zone, positioned in the energy path and in the microtarget path, the microtarget path intersecting the energy path within the irradiation zone;

a beamline, configured to receive radiation generated in the irradiation zone; and

a debris removal arrangement along the micropellet path, downstream of the irradiation zone.

2. The radiation generating system according to claim 1, wherein the solid material is selected to emit radiation in a wavelength in the spectral regions of one of x-ray, EUV, VUV, or UV radiation.

3. The radiation generating system according to claim 1, wherein the microtarget comprises a metal.

4. The radiation generating system according to claim 3, wherein the microtarget material is selected from a group consisting of copper, gallium or zinc.

5 The radiation generating system according to claim 3, wherein the microtarget material is selected from a group consisting of tin, lithium, indium, stibium, or gold.

6. The radiation generating system according to claim 1, wherein the solid target material is an alloy.

7. The radiation generating system according to claim 1, wherein the solid target material is in a solid state at ambient temperature and pressure.

8. The radiation generating system according to claim 1, wherein the microtarget is a micropellet.

9. The radiation generating system according to claim 8, wherein the micropellet has a diameter between 1-200 microns.

10. The radiation generating system according to claim 9, wherein the micropellet has a diameter between 10-50 microns.

11. The radiation generating system according to claim 1, wherein the microtarget is a liquid, liquid droplet, or mist.

12. The radiation generating system according to claim 1, wherein the dispensing apparatus is configured as a microtarget insertion system.

13. The radiation generating system according to claim 12, wherein the micropellet insertion system further includes a plurality of source bins.

14. The radiation generating system according to claim 1, wherein the dispensing apparatus is configured as a solder jet assembly.

15. The radiation generating system according to claim 1, wherein the dispensing apparatus is configured as a supersonic jet system.

16. The radiation generating system according to claim 1, wherein the dispensing apparatus contains pressurized gas.

17. The radiation generating system according to claim 1, wherein the energy source is a laser, electron beam, or proton beam.

18. The radiation generating system according to claim 17, wherein the energy source is a Nd-YAG laser.

19. The radiation generating system according to claim 1, wherein the dispensing apparatus is coupled to a detector system.

20. The radiation generating system according to claim 1, wherein the energy source is coupled to a detector system.

21. The radiation generating system according to claim 1, wherein the dispensing apparatus or the energy source are coupled to a detector system and a firing device.

22. The radiation generating system according to claim 1, further including a bin, positioned to receive microtargets from the irradiation zone.

23. The radiation generating system according to claim 1, further including a radiation chamber, which is operatively coupled to the dispensing apparatus, irradiation zone, energy source, beamline, and debris removal arrangement, wherein the radiation chamber is filled with a gas.

24. The radiation generating system according to claim 1, wherein the debris removal arrangement further includes a circulation system.

25. The radiation generating system according to claim 1, wherein the debris removal arrangement further includes an electric field.

26. The radiation generating system according to claim 1, wherein the debris removal arrangement further includes a magnetic field.

27. The radiation generating system according to claim 1, wherein the debris removal arrangement further includes a hot or cold finger.

28. The radiation generating system according to claim 1, wherein the debris removal arrangement further includes a supersonic jet system.

29. The radiation generating system according to claim 1, wherein the beamline further includes a radiation processing device.

30. The radiation generating system according to claim 1, wherein the beamline further includes a mirror.

31. The radiation generating system according to claim 1, wherein the beamline further includes a window.

32. A method of generating radiation using microtargets, comprising:

selecting a solid material that will generate radiation of the desired wavelength when irradiated by an appropriate energy source;

providing the solid material as a discrete microtarget;

delivering the microtarget into an irradiation zone;

irradiating the microtarget with an energy source along an energy path such that irradiation produces radiation of the desired wavelength;

directing the radiation emitted from the microtarget along a beamline path into a beamline; and

removing target debris from the energy path and the beamline path.

33. The method of generating radiation according to claim 32, wherein the selecting step further includes selecting a material that is solid at ambient temperature and pressure.

34. The method of generating radiation according to claim 32, wherein the providing step further includes forming the solid into a micropellet microtarget.

35. The method of generating radiation according to claim 32, wherein the providing step further includes forming the solid into a micropellet microtarget using a drop tower.

36. The method of generating radiation according to claim 32, wherein the providing step further includes melting the solid material.

37. The method of generating radiation according to claim 32, wherein the providing step further includes forming the solid into a liquid-, liquid droplet-, or mist-shaped microtarget.

38. The method of generating radiation according to claim 32, wherein the delivering step is performed by a dispensing apparatus.

39. The method of generating radiation according to claim 38, wherein the delivering step further includes configuring the dispensing apparatus as a microtarget insertion system.

40. The method of generating radiation according to claim 38, wherein the delivering step further includes configuring the dispensing apparatus as an ink jet assembly.

41. The method of generating radiation according to claim 40, wherein the delivering step further includes configuring the dispensing apparatus as an solder jet assembly.

42. The method of generating radiation according to claim 38, wherein the delivering step further includes configuring the dispensing apparatus as a supersonic jet system.

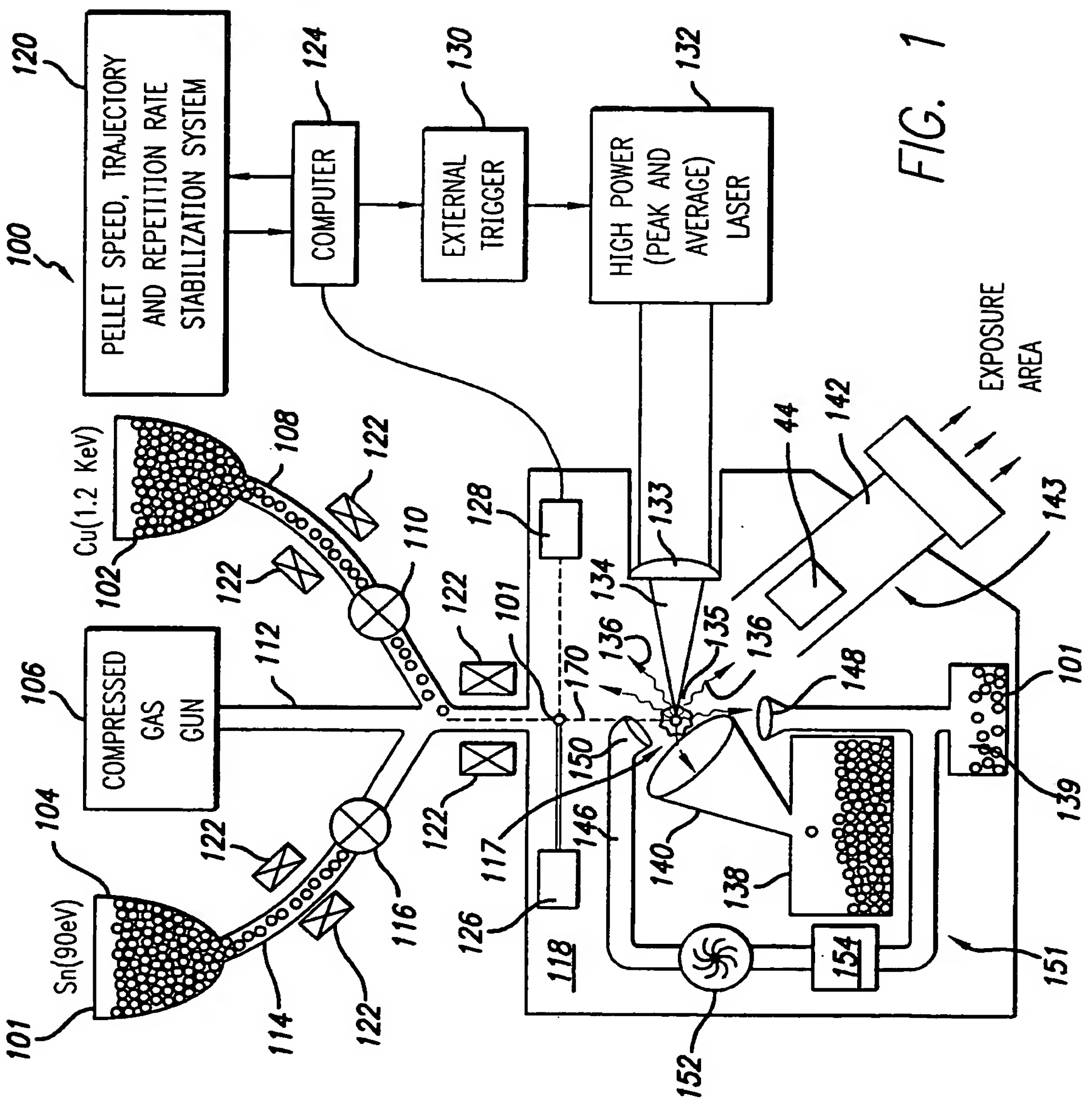
43. The method of generating radiation according to claim 32, wherein the directing step is performed by a mirror.

44. The method of generating radiation according to claim 32, wherein the directing step is performed by a window.

45. The method of generating radiation according to claim 32, wherein the removing step is performed by a debris removal arrangement.

46. The method of generating radiation according to claim 32, wherein the removing step further includes maintaining a higher gas pressure in the irradiation zone than in the rest of the radiation chamber.

47. The method of generating radiation according to claim 32, wherein the removing step further includes using a window.


PELLET SPEED, TRAJECTORY AND REPETITION RATE STABILIZATION SYSTEM
COMPUTER
EXTERNAL TRIGGER
HIGH POWER (PEAK AND AVERAGE) LASER
COMPRESSED GAS GUN
Cu(1.2 KeV)
Sn(90eV)
EXPOSURE AREA
100
120
124
130
132
106
104
101
102
108
110
112
114
116
117
118
122
126
128
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151
152
154
170

FIG. 1

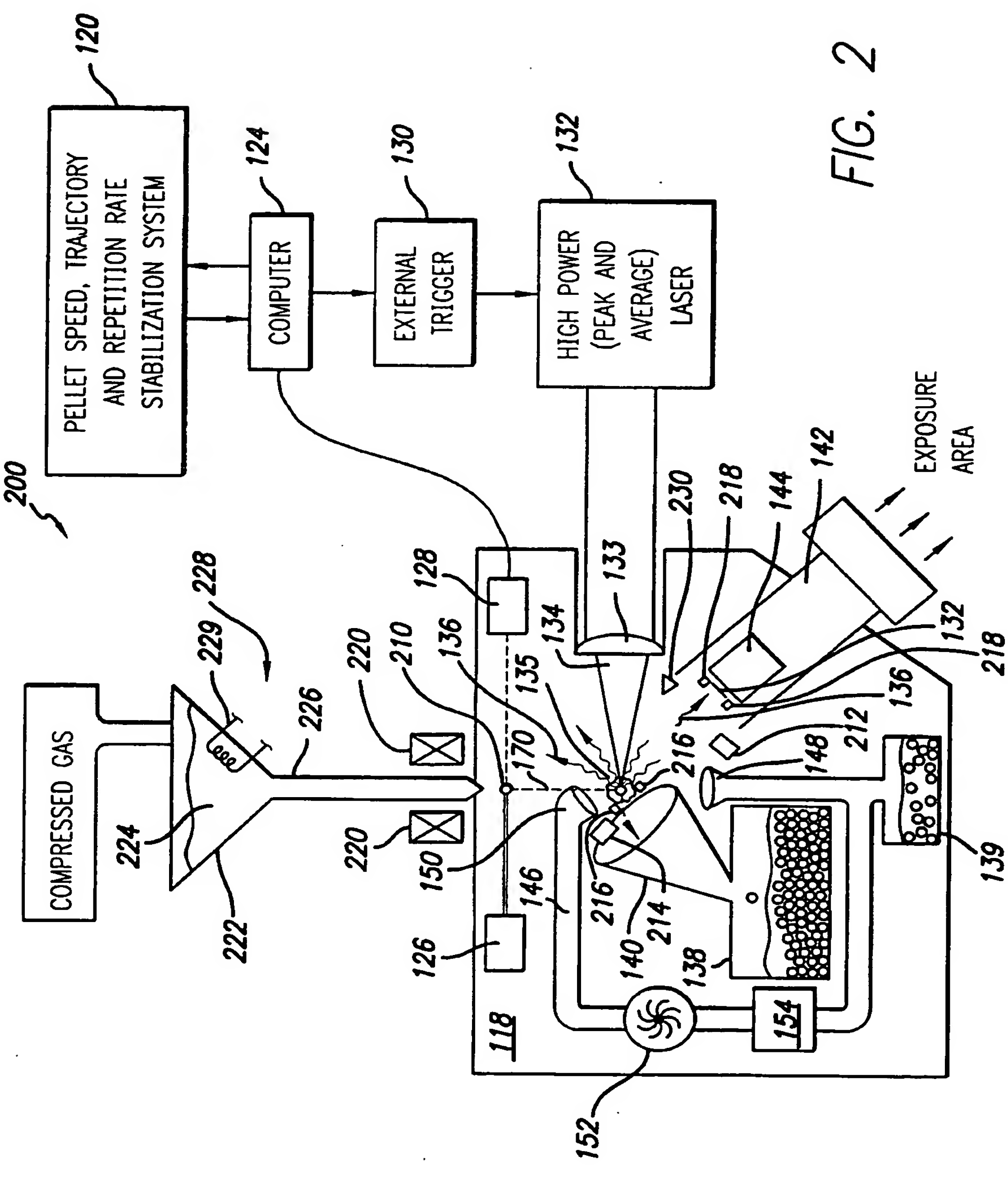
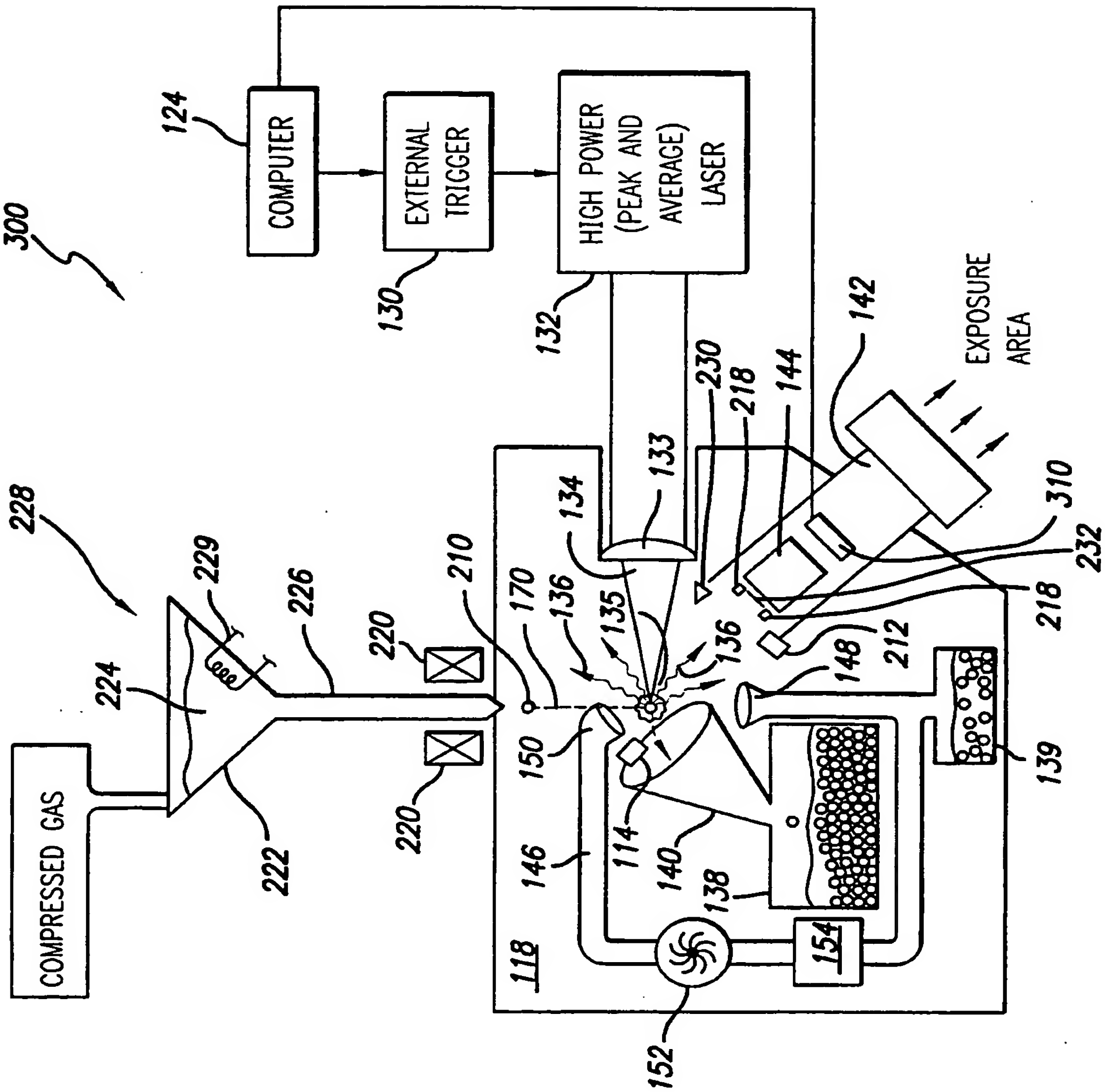

PELLET SPEED, TRAJECTORY AND REPETITION RATE STABILIZATION SYSTEM
COMPUTER
EXTERNAL TRIGGER
HIGH POWER (PEAK AND AVERAGE) LASER
COMPRESSED GAS
EXPOSURE AREA
120
124
130
132
200
228
229
226
224
222
220
210
136
135
134
133
128
170
150
126
146
216
214
140
138
118
152
154
139
148
212
230
218
144
142

FIG. 2

FIG. 3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COMPUTER
124
EXTERNAL TRIGGER
130
HIGH POWER (PEAK AND AVERAGE) LASER
132
133
134
135
136
170
210
230
218
144
142
EXPOSURE AREA
310
232
212
148
139
228
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COMPRESSED GAS
150
114
140
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138
154
118
152

FIG. 4

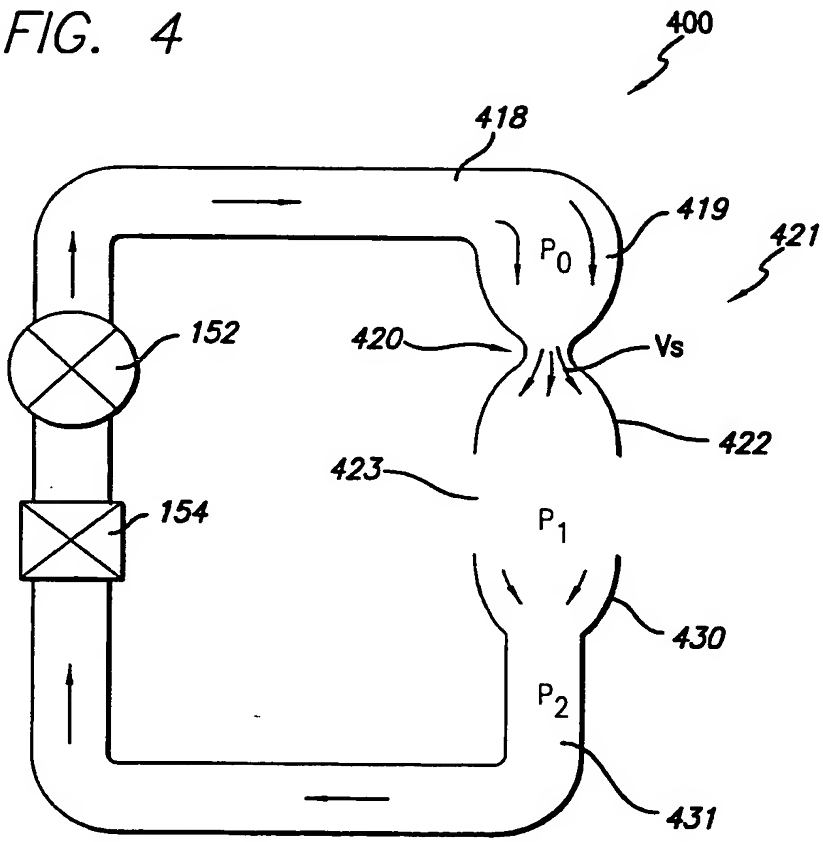
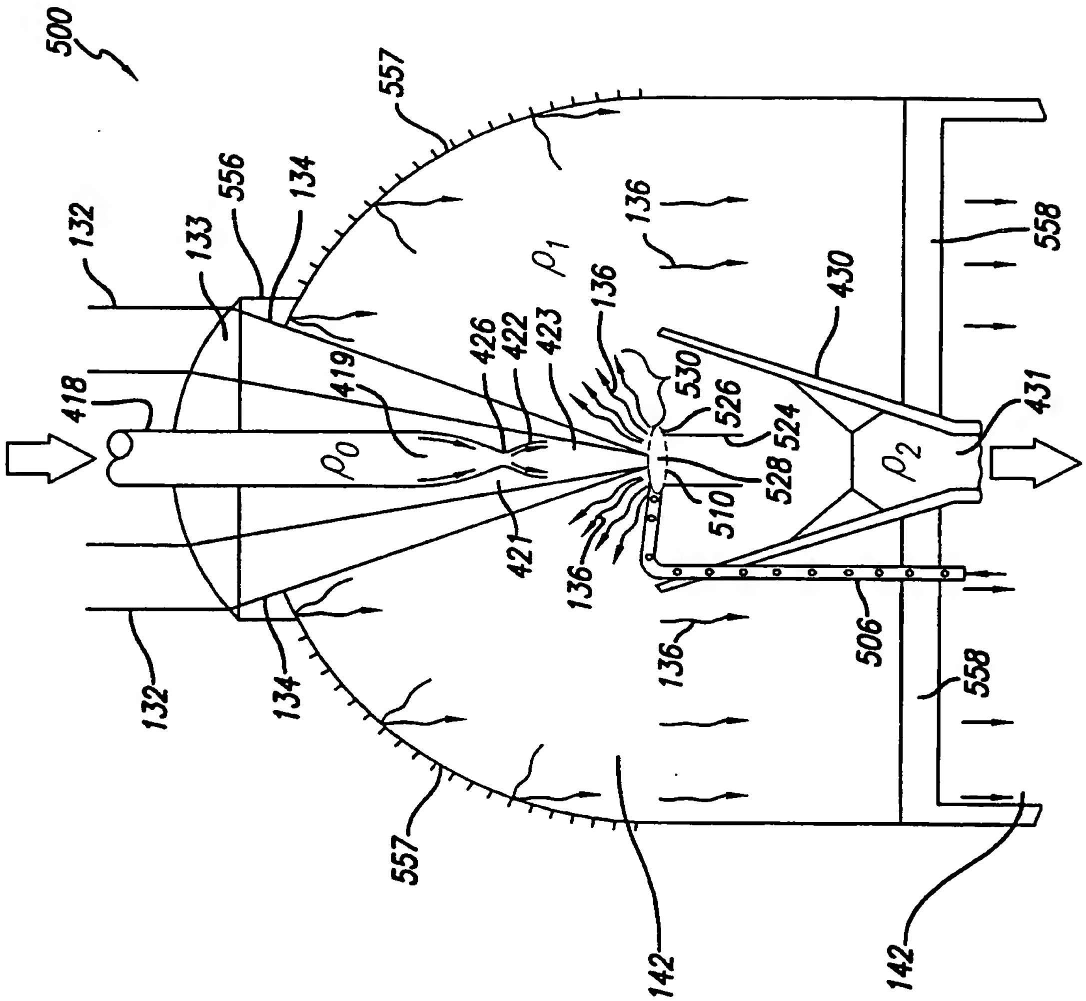


FIG. 5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557
556
134
132
133
418
419
426
422
423
136
ρ_0
ρ_1
ρ_2
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510
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558
421
506
142

FIG. 6

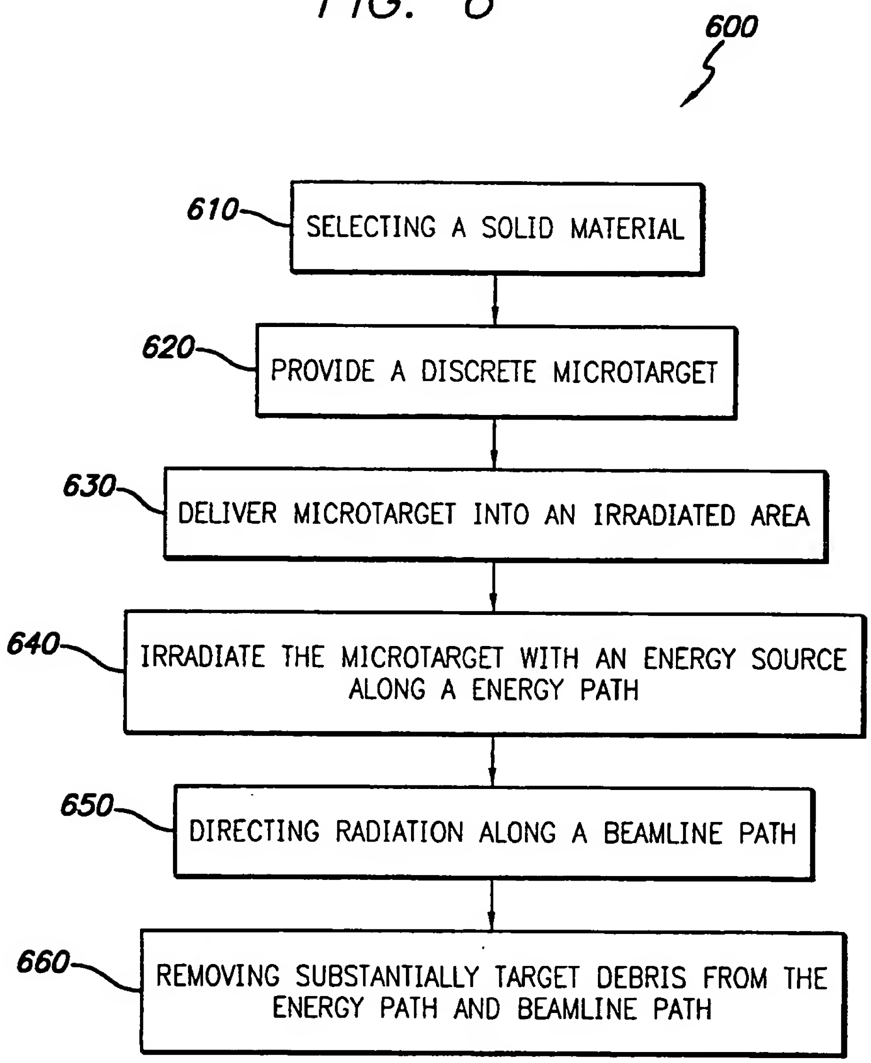
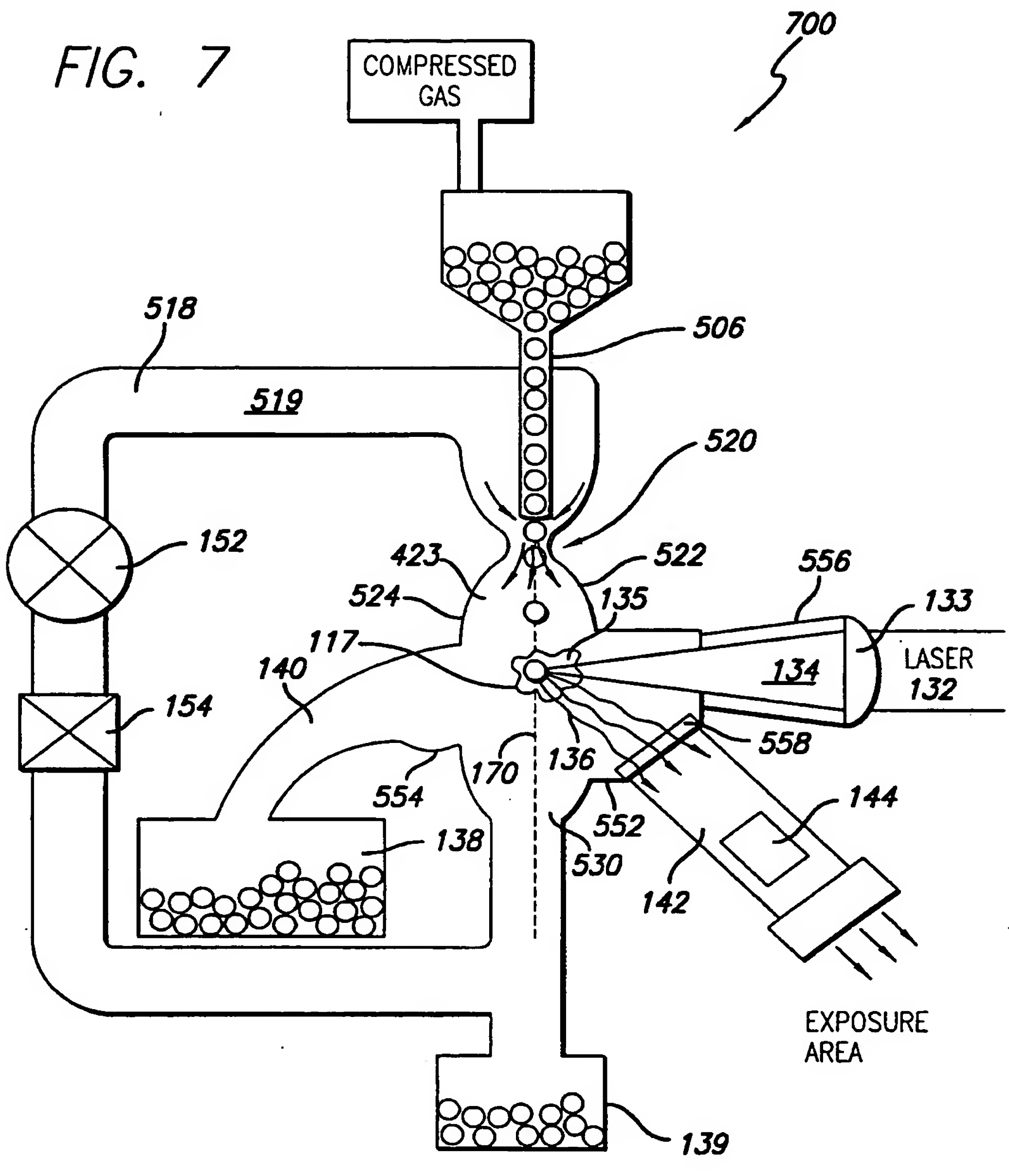

600
610
SELECTING A SOLID MATERIAL
620
PROVIDE A DISCRETE MICROTARGET
630
DELIVER MICROTARGET INTO AN IRRADIATED AREA
640
IRRADIATE THE MICROTARGET WITH AN ENERGY SOURCE ALONG A ENERGY PATH
650
DIRECTING RADIATION ALONG A BEAMLINE PATH
660
REMOVING SUBSTANTIALLY TARGET DEBRIS FROM THE ENERGY PATH AND BEAMLINE PATH

FIG. 7


700
COMPRESSED GAS
506
518
519
520
152
423
522
556
133
524
135
117
LASER
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154
558
136
170
554
144
552
138
530
142
EXPOSURE AREA
139

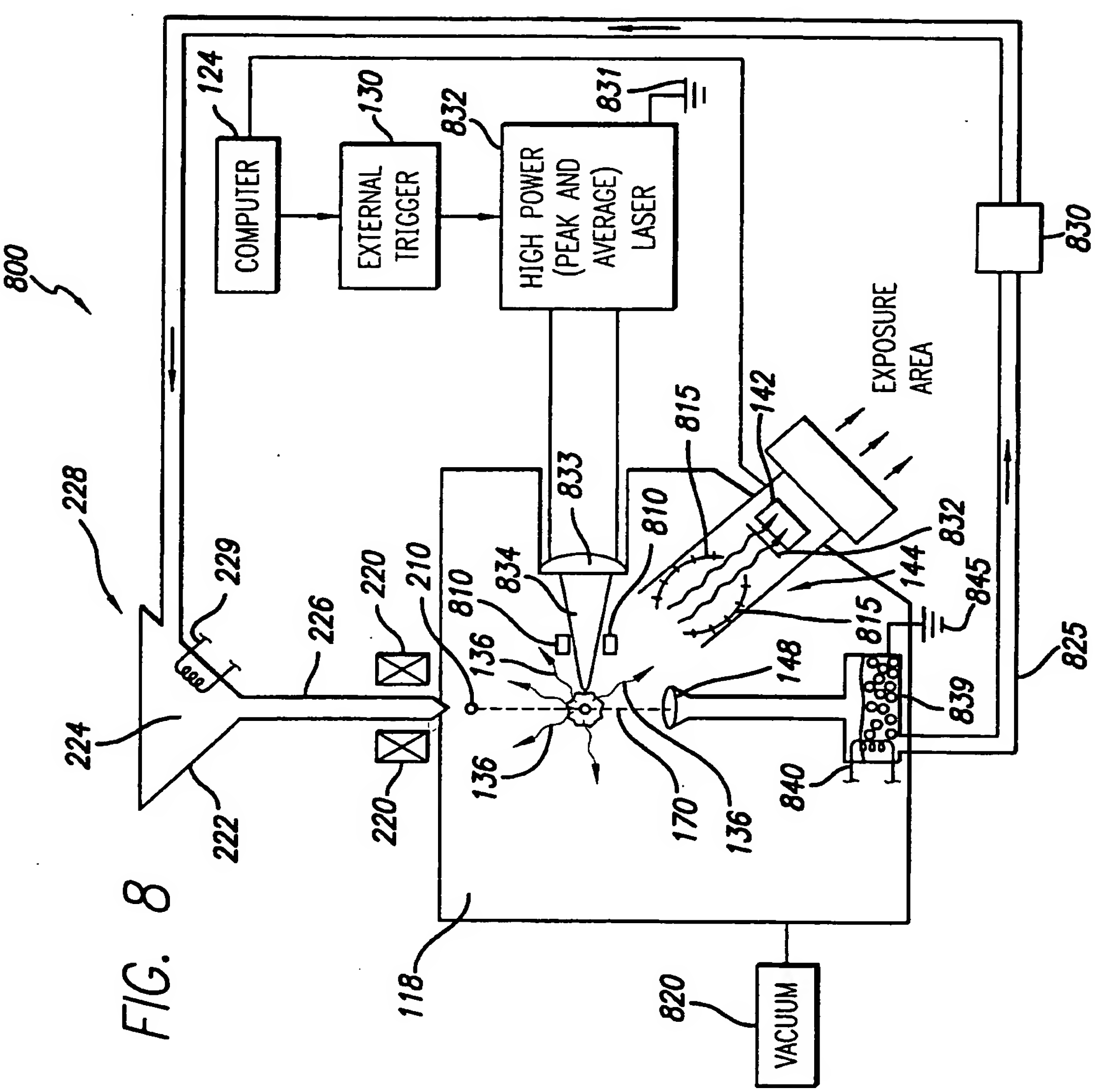
800
COMPUTER
124
EXTERNAL TRIGGER
130
HIGH POWER (PEAK AND AVERAGE) LASER
832
831
830
EXPOSURE AREA
142
815
833
810
832
144
845
825
815
839
148
840
136
170
136
834
810
210
220
229
228
226
224
222
220
136
118
820
VACUUM

FIG. 8

INTERNATIONAL SEARCH REPORT	International application No. PCT/US00/29743

A. CLASSIFICATION OF SUBJECT MATTER

IPC(7) : H01J 35/08
US CL : 378/119, 120, 143

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
U.S. : 378/119, 120, 143

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched
N/A

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)
EAST: MICROTARGET, IRRADIATE, X-RAY, UV, EUV, VUV, LIQUID, TARGET

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	US 4,723,262 A (NODA et al) 02 February 1988 (02.02.1988), all.	1-47
Y	US 4,953,191 A (SMITHER et al) 28 August 1990 (28.08.1990), all.	1-47
A	US 5,052,034 A (SCHUSTER) 24 September 1991 (24.09.1991), all.	1-47
Y, P	US 5,991,360 A (MATSUI et al) 23 November 1999 (23.11.1999), all.	1-47

☐ Further documents are listed in the continuation of Box C. ☐ See patent family annex.

* Special categories of cited documents:

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier application or patent published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search 30 November 2000 (30.11.2000)	Date of mailing of the international search report 29 JAN 2001
Name and mailing address of the ISA/US Commissioner of Patents and Trademarks Box PCT Washington, D.C. 20231 Facsimile No. (703)305-3230	Authorized officer Drew A. Dunn Telephone No. 703-308-0956

Continuation of Item 4 of the first sheet: The title is too long. The new title is, "METHOD AND RADIATION GENERATING SYSTEM USING MICROTARGETS."

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US00/29743

Box III TEXT OF THE ABSTRACT (Continuation of Item 5 of the first sheet)

The technical features mentioned in the abstract do not include a reference sign between parentheses (PCT Rule 8.1(d)).

NEW ABSTRACT

[Briefly, a] A system and method for generating radiation of a desired wavelength is provided by irradiating microtargets (101, 210). These microtargets (101, 210) are selected from any material that will emit radiation of the desired wavelength. A dispensing apparatus (100, 200) delivers a microtarget into an irradiation zone, where the microtarget is irradiated by an energy source (132). The microtarget (101, 210) may be dispensed in liquid or solid form. Once formed, the desired radiation is directed from the irradiation zone to a beamline while debris removal arrangement that is in communication with the irradiation zone (117), the energy source (132), and the beamline (142) substantially prevents debris and other pollutants from contaminating the system equipment.